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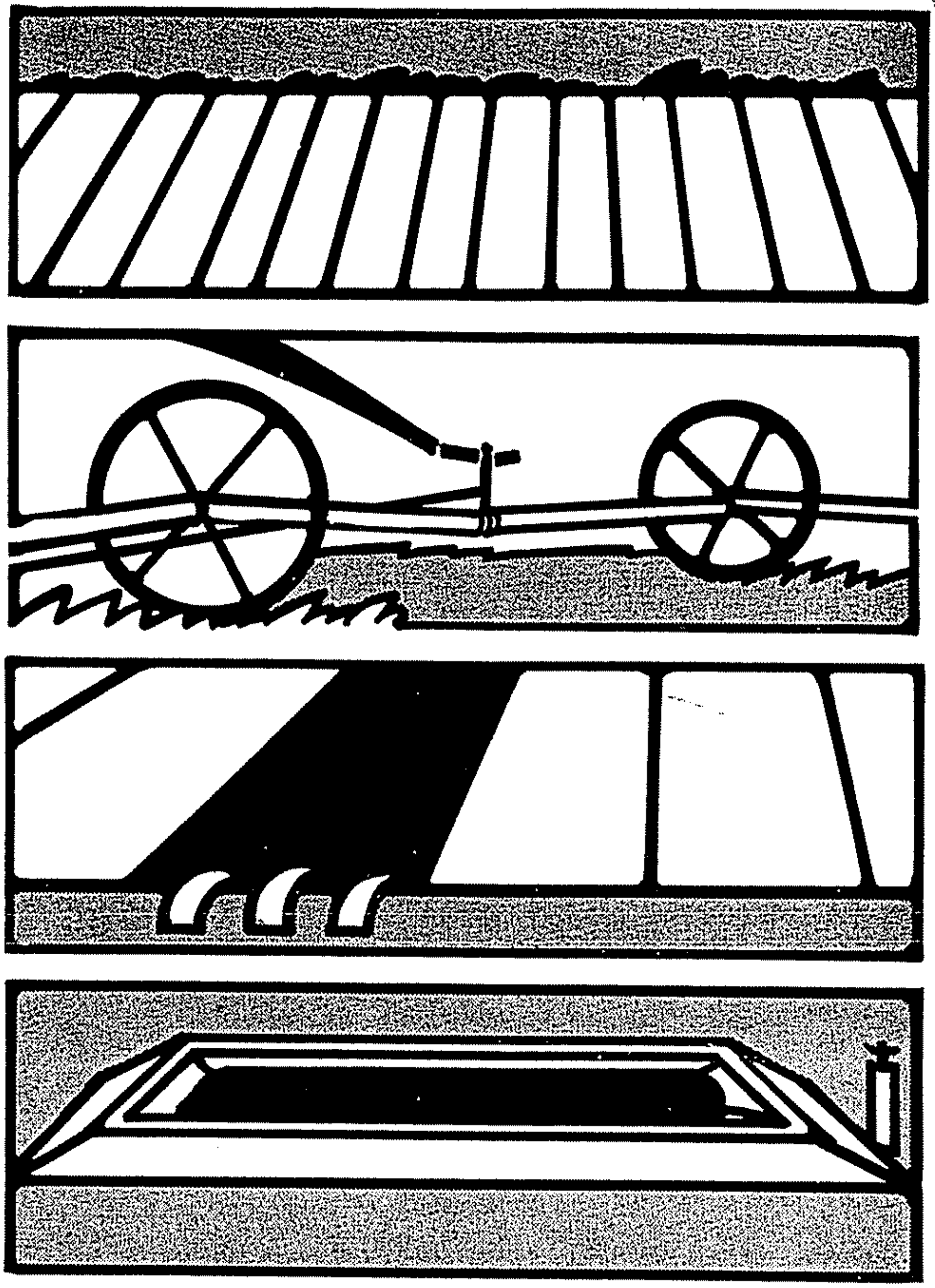

Efficient Irrigation

YOU CAN PLANT MORE LAND WITH LESS WATER

by
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This booklet has been written by Professor John L. Merriam, who, for 20 years before starting to teach, was a practicing engineer with the Soil Conservation Service in Southern California and abroad. He is a registered civil and agricultural engineer and a farmer as well. In 1978 he retired following twenty years of teaching practical and theoretical irrigation classes at Cal Poly, a university noted for its practical approach, and now is doing consulting work at home and abroad.

Preface

The information in this booklet is pertinent all of the time, but as the sub-title suggests it is extremely pertinent in periods of water deficiency. Water saved then can be equivalent to a major on-farm source of water for all but the best irrigator. It would not be so for projects where too deep and runoff losses are recovered for subsequent reuse.

The irrigator who can increase his efficiency from 50% up to 75% can plant half again as much land as he originally expected to. To illustrate: if the water allocation, as used under a typical current 50% efficient program, would satisfactorily produce a crop on 50 acres, a 75% efficient program will produce a crop on 75 acres.

In a drought year, normal irrigation economics must be thrown out the window -- values have changed. One is no longer greatly concerned with the cost of water, labor, capital investment if irrigation efficiency can be increased. The value now lies in terms of additional production from additional land cropped. There is no other single improvement procedure that can provide so great a return and hence justify so much management or capital input.

If one grows a crop that nets $200 per acre and plants 75 instead of 50 acres, the extra return is $5,000. This will justify borrowing the funds to make the needed capital investment for such improvements as a return flow system, a reservoir, pipelines (permanent or portable), and lining the ditches. Equally important is training the irrigator and paying him a salary commensurate with his enhanced ability not just the

METHOD ADAPTABILITY

Method	Soil Uniformity	Infiltration Rate	Ground Slope	Stream Size	Practical Efficiency	Labor	Power
basin	uniform in each basin	any rate	graded to very level	large relative to basin size	75% to 85%	intensive but infrequent	none
basin-check	uniform in each-basin check	any but very slow	mild	large relative to basin size	80% to 90%	intensive but infrequent	none
border-strip	uniform in each strip	any but extremes	mild	large relative to strip size	70% to 90% *	intensive but infrequent	none or low
furrow	uniform in each field	any but extremes	mild or "contour"	medium	70% to 90% *	intensive but infrequent	none or low
sprinklers	may be intermixed	any but slow	any farmable slope	small but continous	65% to 80%	daily or automate	high
trickle	may be intermixed	all but very extremes	any farmable slope	small nearly continuous	70% to 80%	automate	medium

* A return flow system is necessary to obtain the highest values with border-strips and furrows.

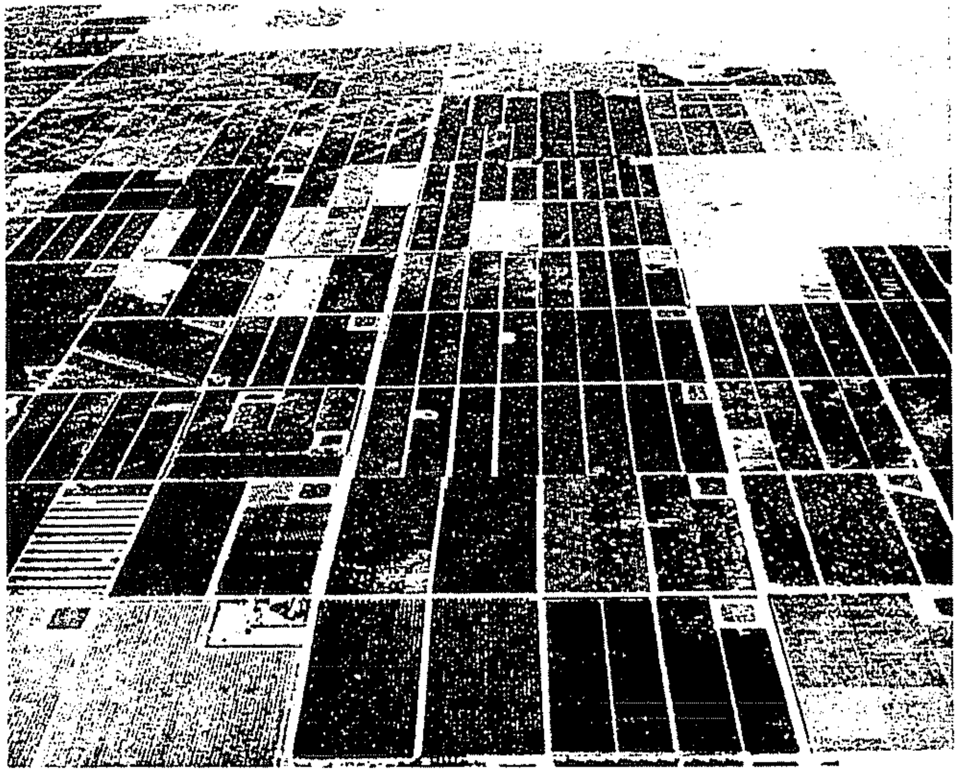
Figure 1

least you can hire a body for, and utilizing professional agricultural engineers, Extension Service people, Soil Conservation Service personnel, or Cal Poly trained irrigation students to make on-farm evaluations of your operation and system to bring them up to the best that is practical. The evaluations may take a couple of days while you are irrigating. Or one may be able to do much of the simpler parts of the evaluation oneself after studying the succeeding chapters.

(A booklet "Irrigation System Evaluation and Improvement," is quite a bit more technical, but would be very helpful for those who will make the effort to study it or who receive help from trained personnel. It is obtainable from Blake Printery, 2222 Beebe Street, San Luis Obispo, CA 93401, for $2.00 tax and postage included.)

The chapters in this booklet first ask the questions to determine whether one can improve his irrigation efficiency (and save labor and power as well as water), and then describe how to do so for the furrow, border-strip, and sprinkle methods. The closing chapter tells about several general practices that facilitate improving effective use of water.

Figure 1, Method Adaptability, on the opposite page, presents general information about where each method can be used and its limitations.



Reservoirs in citrus
Coachella Valley, California

Chapter I

QUESTIONS NEEDING ANSWERS

Where do you fit? Most irrigators are operating at about 50% season-long efficiency (Actual Application Efficiency, AAE). With improved management practices, which in many cases can be easily done, efficiencies can be increased into the 60-70% range. With some capital investment and good management, surface irrigation methods under favorable field conditions, can be increased into the 80-95% range, and sprinklers can be raised up to 75% and possibly 80%. These are Potential Application Efficiency (PAE) values. PAE equals minimum depth stored/average depth applied when everything is just about right. It measures the capability of a system or method and is the only term that may be used to compare them. AAE is defined by the same equation using values found at an actual irrigation. Differences between the two show there is room for improvement usually by management. Low values of PAE indicate need for improving the system.

(The above percent efficiencies, PAE and AAE, are based on the Soil Conservation Service definition of minimum as being the average depth on the lowest quarter of the field, and not the coefficient of uniformity values based essentially on average of lowest one-half.)

Definitions and Terms are described more precisely in the Glossary.

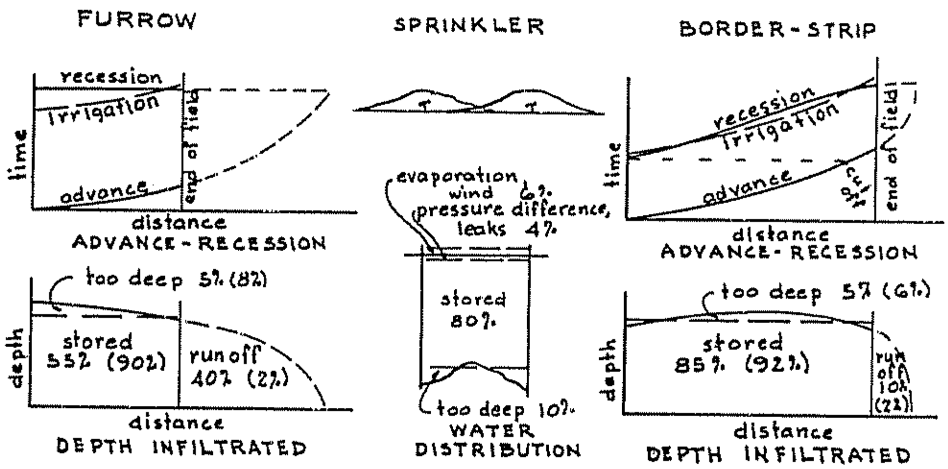

FURROW
SPRINKLER
BORDER-STRIP
recession
irrigation
advance
end of field
time
distance
ADVANCE-RECESSION
too deep 5% (8%)
stored 55% (90%)
run off 40% (2%)
depth
distance
DEPTH INFILTRATED
evaporation wind 6%
pressure difference, leaks 4%
stored 80%
too deep 10%
WATER DISTRIBUTION
too deep 5% (6%)
stored 85% (92%)
run off 10% (2%)

FIGURE 2

The graphs on the opposite page tell the story of what a very good irrigation should be accomplishing. They show where the losses occur and their magnitude when operations are near optimum. For the furrow and border-strip graphs, the advance curve tells the time when the water reached any point down the field and the recession tells when it dried up. The difference between them gives the duration water was at any point infiltrating into the ground. The irrigation curve tells how long water should be at any point. The dotted lines past the end of the field represents water running off.

Below these curves are the depth infiltrated curves. They show the depth of water infiltrated in the time interval plotted above. By proportions of the areas, the distribution of the water can be found and expressed as a percent of the total as shown on the figures. When there is a return flow system (numbers shown in parenthesis), the run-off water can be reused so the only loss is to too deep. The too deep loss is a small amount contrary to what many people believe simply because intake rate decreases with time and very little is infiltrating towards the end of irrigation even though quite a bit of time may elapse.

The sprinkler distribution is independent of the soil intake rate so only a depth infiltrated curve is needed, and there is no decrease in the loss rate with time.

A full evaluation of an irrigation will furnish detailed information and provide the basis for economic decisions. However, the following questions will serve to show the magnitude of the easily obtainable increases in efficiency and the following chapters how to do so.

Fundamental to all irrigation methods are certain essential conditions. "Is it dry enough to irrigate?" and "Is it wet enough to stop?" To properly act in response to these questions requires a water supply that is flexible in frequency, rate, and duration. When the water supplier can't do this, on-farm reservoirs are in order. The photo of a portion of Coachella Valley, which has the highest per acre yield of any USBR project, shows what farmers with expensive land feel is the relative value of productive land versus a reservoir. One properly designed reservoir and distribution system can serve 80 to 160 acres and save much water and labor.

The question "Is it dry enough to irrigate?" - in other words, has the soil moisture deficiency become equal to the Management Allowed Deficiency (MAD), which is the optimum dryness. This question is now being widely answered by the Irrigation Management Service (IMS) program available through many irrigation districts and irrigation consultants. It can also be done by the irrigator making soil moisture deficiency checks using a soil auger. This simple technique will be covered in the last chapter.

The question "Is it wet enough to stop?" can be determined by probing the depth of penetration of the water during irrigation and turning it off at the proper time when the soil moisture deficiency has just been satisfied. Flexibility of Duration is important since all water run after this moment is 100% wasted except for surface irrigation methods utilizing a return flow system.

Now with this background, the irrigator can begin finding his own irrigation efficiency by subtracting from the very high but attainable Potential Application Efficiency (PAE) values shown on the graphs -- 90% for furrows, 85% for border-strips, and 80% for sprinklers -- as follows:

-- If you always run water for 12 or 24 hours or some other fixed number of hours instead of turning it off at a time based on a field check, subtract 10% to 20% or more efficiency points. This is usually the single biggest loss for most systems and especially for sprinklers. (For example, if the system were designed to run 24 hours but 20 hours would have been adequate, one would lose (24-20)/20 = 20%. (Turn it off!) If your crop never shows moisture stress anywhere, you are never under-irrigating so on the average you must be over-irrigating, lose 5%.

-- If you are using surface irrigation and don't have a return flow system, take off 20% to 40% for furrows, or cut back the stream and lose only about half as much. Furrows really need a return flow system to save water and labor. For border-strips don't take off any more as that loss is included in the original figure, but you could save 5% to 15% if you did have a return system or, on sandy soils, carefully pond the water at the lower end. (Invest some capital!)

-- For a sprinkler system designed to run 12 hours, do you make your night run shorter than the hotter, windy day run by an hour or so or alternate the sets to compensate? No, then take off about 3%. Do you have leaking gaskets, old and new nozzles on the same line? Yes, then take off 5%. Have you used a pressure gauge at various locations in the system to see if pressures are reasonably uniform <u>and</u> at the design value -- do you know the design pressure? No, take off at least 5%. Do you open the line valve wide open for all sets? Yes, take off 5%. Do you tip the sprinkler risers along the edge of the field so that instead of wetting the road you put that water in the field for your crop? No, take off 1% or 2%. Do you use the alternate set procedure when you move your line at every other irrigation? No, take off 5% or more. Do you operate in a hot, dry climate? Yes, take off 5 to 10%, and 5% more if it is very windy. Does the sprinkler jet from one set reach or nearly reach the location of the previous lateral location? No, lose 5%.

-- For furrows, do you use a small stream, which takes a long time to reach the lower end (Advance Ratio 1:1) and so over-irrigate the upper end, but gives very little run-off to be saved by a return flow system? Yes, subtract 15 points. [Advance Ratio (AR) = Time of Advance needed to reach the lower end/Time of Irrigation needed to infiltrate desired depth at lower end.] Do you use a large stream to reach the end quickly (Advance Ratio 1:4) and so have very little too deep but do have lots of run-off and no return flow system? Yes, lose 30% to 40%. Same as above but do have a return flow? Yes, lose no points. The equivalent to a large stream is a short furrow since the Advance Ratio is the key to limiting excess deep penetration at the upper end.

-- For both surface methods, do you have dissimilar soils and intake rates along a furrow or strip? Yes, lose 5% to 10%. Do you have 24-hour water deliveries and no reservoir? Yes, lose 10%.

-- For border-strip irrigation, do you have water on the upper and lower end of the strip for about the same duration? No, lose 5% to 15%. Do you turn off the water when the stream is more than .6 to .7 of the way down the field for the finer textured soils or more than about .9 for sandy soils so that run-off is excessive? Yes, lose 5% to 15%.

If these questions and answers convince you that efficiencies can be improved then you can save water and labor. And remember that it is not the cost of water and labor that counts in a dry year, but how much more crop can be produced with a limited water supply by planting more area with water conserved because of increased efficiency.

The subsequent chapters describe in detail how to operate to attain the higher values by making one's Actual Application Efficiency (AAE) approach or equal the Potential Application Efficiency (PAE).

Chapter II

MANAGING THE FURROW METHOD

Water is lost in furrow irrigation in two ways -- it runs off and it goes too deep. Stopping or reducing these losses conserves water, and usually labor and energy. In areas where more land is available than water to irrigate it, the value of this water is measured by how much crop it can produce, and the cost of it and the labor and capital to apply it ceases to be of dominant economic importance. Efficient irrigation under such conditions is of great value.

Basic to all irrigation are two questions -- "Is it dry enough to irrigate?" and "Is it wet enough to stop?" The techniques for answering these questions will be covered in Chapter V, but the importance of doing so and the effect on the operation of furrow irrigation systems will be illustrated here.

For furrows, runoff and uniformity of the depth of water infiltrated along the furrow are related to the speed of water reaching the lower end (Time of Advance) relative to how long it needs to be there to do a job of soaking in enough water (Time of Irrigation). This is conveniently expressed as the Advance Ratio (AR) -- the ratio of the Time of Advance (T_{adv}) to the Time of Irrigation (T_i) ideally, otherwise to T_o.

If a large, but non-erosive, stream is turned into the furrow it will reach the lower end quickly if the length is reasonable. The water will be on the upper end only a little longer than at the lower end and a very uniform irrigation will result. This uniformity is measured by the Distribution Uniformity:

$$DU = \frac{\text{average depth infiltrated in lowest quarter of field}}{\text{average depth infiltrated on whole field}}$$

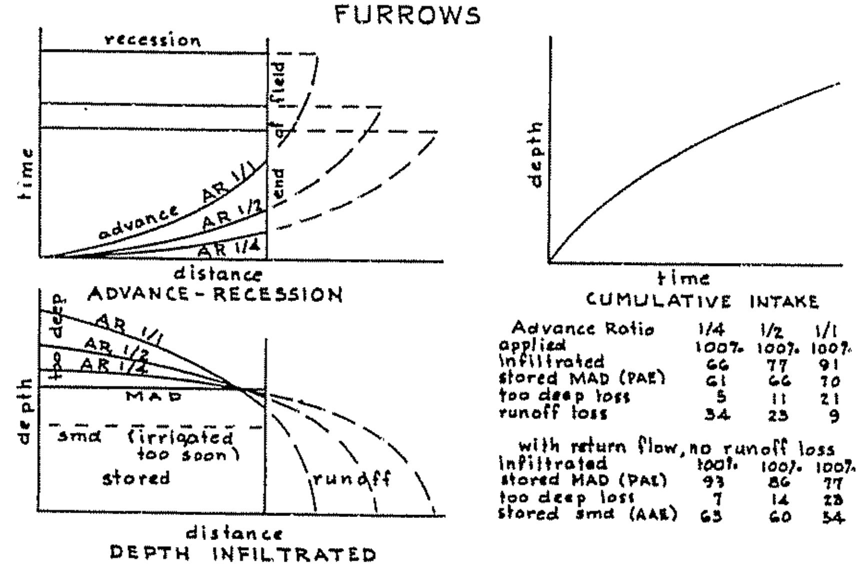
The same effect can be obtained with a smaller stream and a shorter furrow. However, if this relatively large stream continues to run full size for a number of hours more in order to irrigate the lower end, there will obviously be lots of runoff.

There are several management tools to adjust these conditions to get the best results. Changing the Time of Advance by changing the stream size is the easiest thing to do to affect the Advance Ratio and hence the uniformity. The largest usuable non-erosive stream will give the best uniformity. Adjusting the length by using gated pipe across the middle of the field, or other ways, may often be practical. Reusing old furrows rather than making new ones each time lets the water move faster, reducing the Time of Advance.

Varying the Time of Irrigation, the other factor in the Advance Ratio, can be done several ways including changing the desired soil moisture deficiency at the time to irrigate (Management Allowed Deficiency, MAD), changing the furrow spacing or its shape, reusing furrows or making new ones, etc. Other things such as driving the tractor wheels or pulling a drag down each furrow may be helpful in reducing the intake rate. Chiseling often is done in a way which results in a different effect in different furrows and it usually increases intake rate. Both of these latter items tend to make irrigation less uniform.

The graphs of Cumulative Intake, Advance and Recession, and Depth Infiltrated shown on Figure 3, are taken from a field evaluation on a compact sandy loam. They are modified only slightly to better illustrate the concepts. They indicate the relative effects of changing stream size to affect the Advance Ratio and the losses going too deep and running off, and the amount that is stored for crop use. Not indicated is the effect on changing length. A shorter furrow with other conditions constant, will result in a smaller AR.

FURROWS



Advance Ratio	1/4	1/2	1/1
applied	100%	100%	100%
infiltrated	66	77	91
stored MAD (PAE)	61	66	70
too deep loss	5	11	21
runoff loss	34	23	9
with return flow, no runoff loss			
infiltrated	100%	100%	100%
stored MAD (PAE)	93	86	77
too deep loss	7	14	23
stored smd (AAE)	63	60	54

FIGURE 3

The Cumulative Intake curve simply indicates at any time the depth of water that would have infiltrated into the soil for the particular furrow shape and spacing that was tested. From such a test, presuming reasonably similar conditions at the next irrigation, a good estimate can be made of how long water would need to be near the lower end (average of the lowest quarter) to satisfy the desired soil moisture deficiency (MAD). Or if one knows how long the water has been at a spot, a reasonable estimate can be made as to what amount of water has infiltrated.

The Advance Curve shows how fast three different size streams would go down the furrow. They have been drawn so that the time it takes them to reach the end (Time of Advance) is 1/4 and 1/2 of and the same as (1/1) the Time of Irrigation.

This represents a range from quite rapid advance to moderately slow corresponding to Advance Ratios of 1/4, 1/2, 1/1. The results of these variations are shown in the table with the curves, Figure 3. It should be studied for trends and magnitudes.

For the irrigations indicated, which were turned off when it was just wet enough to stop, for the AR of 1/4, the percent lost to too deep was 5% of the total water applied, lots of which ran off, for the 1/2 AR, 11% was lost, and for the 1/1, 21% went too deep. Remember there are a number of ways to affect the AR to make it and the too deep loss what you want them to be, and the loss can be kept smaller with furrows than with any other method.

Now, let's look at another too deep type of loss. If it isn't "dry enough to irrigate," but one thinks it is and applies the regular irrigation, lots of water may go too deep. Water cannot be stored in the soil in a greater amount than there is dry soil in the root zone to hold it, i.e., greater than the Soil Moisture Deficiency (SMD), so check it before deciding to irrigate. Graphically, on the Depth Infiltrated curve, all the space above the SMD line now is lost to too deep and the AAE shown in the table is low.

This can be partially alleviated by acting in response to the second question, "Is it wet enough to stop?" If the water were turned off when the depth of water infiltrated at the lower end equalled the SMD rather than at the planned MAD, the loss to too deep from over-irrigation would be eliminated. However, it would start a chain of consequences. The Time of Irrigation would be reduced. This would increase the Advance Ratio. That would result in a larger percent of water infiltrating at the upper end relative to the lower end. However, the effect of all of this could be overcome by using a shorter furrow or a larger initial stream to have the same AR.

To summarize these seemingly involved, inter-related procedures, if you want to put on a lighter irrigation use a shorter furrow, or a large enough stream to get to the lower end with a reasonable AR, and turn it off on time -- the same as one would do for any good irrigation. For annual crops with an expanding root system, an early, light application can easily be done by using gated pipe across the middle of the field effectively shortening the length. The upper and middle lines should be run simultaneously to avoid double irrigation at the middle line. The full length can be used for the heavier, later irrigations. Or the light early applications can be made longer by including part of the "pre-irrigation" depth.

Furrow spacing has a very definite effect on Time of Irrigation. It simply takes longer to move water further out to the side and it goes slower and slower the wider the spacing. Since it is taking longer, it is also going deeper. This all means that if one is putting on light applications one needs furrows closely enough spaced to wet across below the surface during the shorter time. If one is putting on deep irrigations, a wider spacing is allowable. It will then take a great deal longer, perhaps even three times longer, to do the job. This will permit the use of longer furrows at high efficiency. Spacing is also related to soils and can be adjusted to crops and equipment.

Similar management changes can also be accomplished by changing furrow shapes. Vee furrows may be wet 10" wide, a parabolic one may be wet 15", and a broad one which is level across may easily be 24" wide. Since the water moves sideways about the same distance from the edge of all shapes, the area wet, the time of irrigation, and the stream sizes are all correspondingly adjustable.

Looking at the other loss -- runoff -- which may easily be very large, one again finds that it also is related to the Advance Ratio with all of its inter-ties to initial stream size, furrow shape, spacing and length, and MAD and their side effects. The curves and table showing the advance relationships and the Depths Infiltrated indicate that for a rapid advance, AR of 1/4, there is lots of runoff, 34% of all applied water if the water is turned off on time. For the smaller streams, AR of 1/2, it reduces to 23%, and for the quite small streams (which would be similar to a longer furrow and the larger stream) the runoff is small, 9%, but this is also the one that lost 21% too deep.

The runoff loss can be reduced by about one half or more by making one or two cutbacks in the stream size. The first cutback should be made an appreciable time after water is running past the lower end when the loss has become big enough to warrant cutting it back. If it is done sooner as is often suggested, the lower end will be inadequately irrigated and the runnoff at the end of irrigation will be greater. The most economical operation with one cutback is such that the runoff at the time of cutting back is about the same as it will be at the end of irrigation. If the cutback is done in conjunction with the use of a cycling type return flow system, the above cutback operation will minimize the cost and power requirement.

A return flow system should almost always be part of a furrow irrigation system. Ordinarily, it is economically justified as a labor saving device as well as water saving. When the value of water is measured in terms of its productivity, a return flow system back to an irrigation reservoir, is practically the first item to be considered. Using one in conjunction with small Advance Ratios, the Actual Application Efficiency (AAE) values should approach the Potential Application Efficiency (PAE) of about 90% if the soils are uniform and the water is cut off on time.

In order to do this last item, a reservoir may be essential if water deliveries are for units of twenty-four hours.

A gravity reservoir in conjunction with a large capacity semi-automated delivery system is a real labor saver as well as helpful in conserving water since it makes it possible to set all the furrows in a field at one time and to make cutbacks as desired. It also serves as regulating storage for the return flow system.

In summary, furrows on reasonably uniform soils and slopes are the most efficient method of irrigation if proper management uses a small Advance Ratio, turns water off on time, and utilizes a return flow system. Low efficiencies are not the fault of the method, but of management.

Chapter III

MANAGING THE BORDER-STRIP METHOD

Border-strip irrigation has several other common names - border, check, strip check, flood. In addition, it is the most widely used method in California and the least understood. It has a high Potential Application Efficiency (PAE), 80% plus, but is usually operated at about 50% Actual Application Efficiency (AAE). Furthermore, it has the dubious distinction, seldom realized by its users, of being the most sophisticated, complicated, least adjustable method. But when border-strip irrigation is used correctly, AAE can go above 90%, and labor and power requirements are very low.

Because of the complications in obtaining real high efficiency, each border-strip has only one Management Allowed Deficiency (MAD) value, plus or minus a little, that is just right. For this reason, it is best adapted to permanent crops such as pasture, alfalfa, orchards, etc. With good management and planning, it can be made to do very satisfactorily for many deep-rooted annual crops.

This recalcitrant paragon is described as a sloping strip of land fairly level across, which is bounded on the side by borders (dikes, ridges). The soil for the length of the strip should be uniform but one can live - at lower efficiency - with some variation. If the strip is graded to a uniform grade or nearly so, lengthwise and across, it is called a graded border-strip.

Where soils are too shallow and somewhat undulating and much grading is not practical, guided border-strips are feasible. For these, the grade along the strip is allowed to vary to conform somewhat to topography, and the strips are made narrower so they are easily made level across. They often run nearly straight down hill. (The true objective of land grading is not to create a plane surface, but is to improve irrigation.)

To understand the limitations and management of border-strips, one can best start from the optimum conditions as shown in the adjacent graph, Figure 4. The Cumulative Depth Infiltrated curve indicates the depth of water infiltrated from a ponded condition after any length of time as found from a field evaluation test. It can be approximated from studies on typical soil textures.

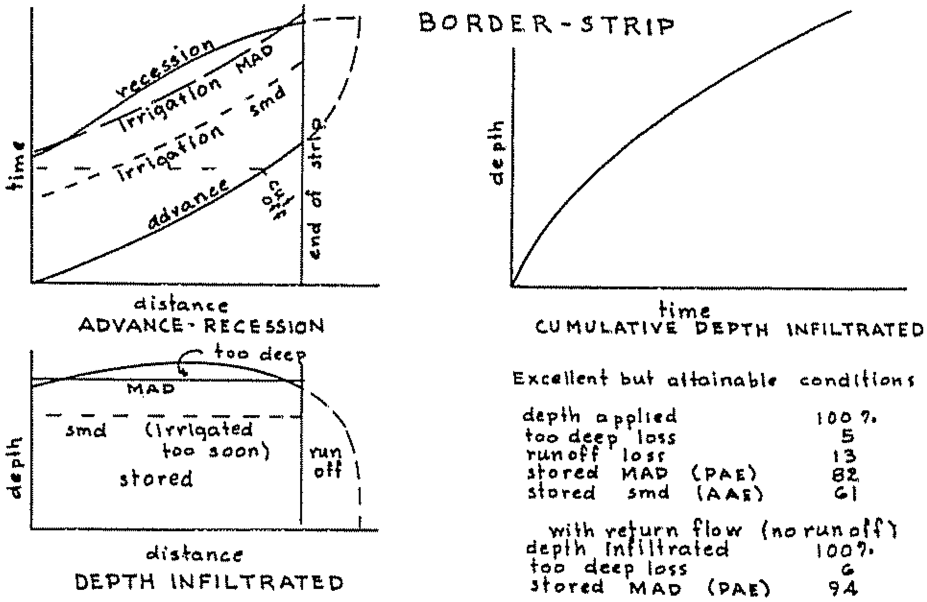


Figure 4

The Advance and Recession curves are respectively plots of the time it took the water to move (advance) down the field to various points usually each 100 feet apart, and the time when water disappeared (receded) from the various places. The duration of time water was at any location with an opportunity (To) to infiltrate there is the increment of time between the two curves.

By using this time of opportunity in conjunction with the Cumulative Depth Infiltrated curve, the depth corresponding to the increment of time at each location along the strip can be found. The plotting of this depth and distance is the Depth Infiltrated curve from which by proportion, the losses and stored percent and depths can be determined.

The detailed procedure for obtaining all of this information requires making a field evaluation. That process, which is moderately involved, is described in the booklet "Irrigation System Evaluation and Improvement," mentioned in the Preface.

However, the simple procedure of timing how long it takes water starting at the upper end to reach the middle and lower end of the strip, where it was and when it was cut off, and when water is no longer on the surface at the top, middle, and bottom (with or without ponding) is just a matter of observation. From this information, the Advance and Recession Curves can be sketched. If distance units of 100' are used, better curves can be developed.

The graphs shown represent a real good job of irrigating - better than can be done every time. However, measured tests have given values better than this. Poorer, but easily improved conditions, are described later.

The ideal condition for uniformity exists when the Advance Curve has been made "parallel" to the Recession Curve. For this condition, about the same time of opportunity occurs at each end with some extra in the central portion. The times are made about the same by simply turning in the stream size that moves at the desired speed. The slope of the Advance Curve is adjustable with stream size, but the slope of the Recession Curve is fixed. This is true because the water that is just disappearing at any point by infiltrating or moving on, is always doing so under the same physical condition for each specific strip. Since the Recession Curve is fixed in shape, it becomes the control item for border-strip irrigation. This is a distinguishing and unique condition. The time at which the recession starts is controlled by when the water is turned off plus a little more (Lag Time) taken by the several inches of water ponded at the top to drain off and infiltrate.

The depths infiltrated will vary appreciably less than the time difference between the Advance and Recession because any extra time is at the end of irrigation when the infiltration rate is the slowest. This is illustrated by the Cumulative Depth Infiltrated Curve. Very uniform infiltration along the strip is possible. The table shows for this illustration that only 5% went too deep because of the non-uniformity. Up to 10% is a reasonable loss.

Runoff loss is largely controlled by how far back from the lower end the water is when it is turned off. Where it should be is related in a complicated way to ground slope, stream size, flow rate, strip length, Soil Moisture Deficiency (SMD), soil conditions, crop conditions, soil and water temperatures, etc. The practical answer is by trial and error knowing the objective which is to turn the water off late enough to have the 3" to 6" depth of ponded water in the upper part of the strip flow on down to the end and adequately irrigate there, but not so late that too much flows on by the end and runs off. On fine textured soils with low gradients and long strips this may occur about .6 the way down the strip. For medium textures, it is often .7 to .8 down the way, and on high intake rate soils it will be near the end.

Irrigation is an art and a science. This part is art. With adequate art, the runoff loss is about 10% to 15%. A return flow system eliminates most of the art needed as well as the runoff loss.

In summary of losses, the too deep loss is low and uniformity is high if the Advance Curve is made about "parallel" to the recession by simply using the right size stream, and the runoff loss is small if the water is cut off at the correct distance.

Now comes the intransigent part imposed by this excellent method. Up to here nothing has been written about the two basic questions, "Is it dry enough to irrigate?" and "Is it wet enough to stop?" They must be answered.

The irrigation curve (MAD) drawn in conjunction with the Advance and Recession Curves is drawn parallel to the Advance Curve and above it by the time it takes to infiltrate the desired irrigation (MAD). It represents a specific time related to a specific depth of water as taken from the Cumulative Depth Infiltrated Curve, and only at the ends is it just barely below the recession in order to have the minimum depth infiltrated show up as the average of the lowest quarter of the field. If a different depth, and related time, were desired, a different line would be drawn which would be above or below the Recession Curve and so would therefore represent under or over irrigation. There is no way that the excellent condition first presented can be maintained except for the original MAD. However, reasonable compromises with near perfection can be very good.

With the border-strip method only four things are adjustable, and the last of them is often not practical. They are the stream size affecting the advance rate and uniformity, the MAD affecting the duration water should be on, the distance and time at cutoff, and the length of the strip. Compromises, but at reasonable efficiencies, are essential.

Illustrations of less than the best will be helpful in identifying problems and what may often be done to correct them. Since the scope of this booklet is limited, appreciable study may be needed to fully appreciate the complexities. (Additional illustrative curves are included in the Appendix.)

The first illustration is shown in Figure 4 and the table. If the question "Is it dry enough to irrigate?" is improperly answered and full irrigation is applied four days too soon as represented by the SMD line, the Actual Application Efficiency (AAE) drops from 82% to 61%. If this were standard procedure, (.82-.61)/.61 = 35% more land could be planted with the water saved by irrigating four days later when the soil is dried to the MAD.

If one is among the unfortunate irrigators who must take their water too soon, because of rigid schedules, then the following compromises must be made: the date of irrigation being fixed, one will irrigate at the small SMD existing at that date and try to be reasonably efficient in applying that depth of water. Since the reduced depth takes less time of irrigation, the stream should be near the lower end faster than before. This will require a larger stream. The Recession Curve, that inexorable control item, does not change its shape so water is at the lower end longer than at the upper end and more runoff may occur. This condition is represented by the curve titled Stream Too Large in Figure 5. The graph shows that it is quite possible to over-irrigate the lower end of a strip, or under-irrigate the upper part. The identifying feature for too large a stream is the divergence of the Advance Curve from the Recession rather than being "parallel."

The graph, as drawn, corresponds to about 20% water lost to too deep and 15% to 20% running off for a 60% to 65% efficiency. This is not too bad. With a return flow system it is a respectable 80% even though the stream was too large.

The next graph representing too small a stream - a very common problem - is diagnosed by having the Advance Curve converge toward the fixed Recession Curve. If one has a fixed stream of water as from a well, the strip can be made narrower to increase the effective stream size. With the moderately smaller stream condition shown, very little runoff occurs, -5%,

GRAPHS OF UNDESIRABLE CONDITIONS

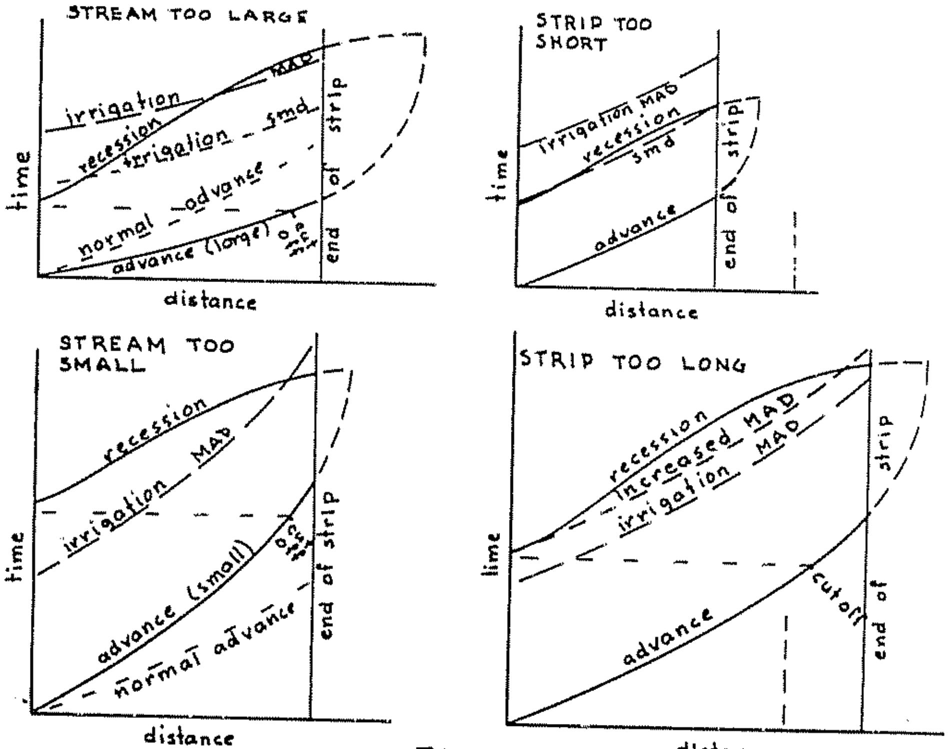


FIGURE 5

and the too deep loss is about 20%. AAE would be a respectable 75%. This may be a fairly good compromise if a return flow system is not utilized. If much too small a stream is used, results will be very poor.

When the strip is too short, as shown by the graph, only a much smaller SMD can be used or losses are excessive. This is to be emphasized - border-strips are NOT adaptable to short fields, and very seldom is efficiency improved by just shortening the length. This latter advice is often given, but it is incorrect. It does apply to furrows, but not to border-strips unless other factors such as MAD are drastically changed.

Basins may be used to replace short border-strips.

The last of the graphs on Figure 5, shows conditions when the strip is too long. As before, the stream size is the desired one to keep Advance and Recession Curves parallel. The graph indicates that a larger MAD is needed because the stream must be run longer to go the greater length and be turned off later. A larger stream would also be a compromise technique with this longer strip. Very long strips are feasible if large MAD values are used.

For annual crops with an expanding root system, the early irrigations are usually light with deeper ones later. With border-strips, the light ones would not be efficient. Two management alternates are practical. The early irrigations can be made larger than needed with the excess being used in lieu of a pre-irrigation. Or portable pipe can be used to cut the length in half for the first part of the season and then removed to use the full length for the larger, later irrigations.

The question "Is it wet enough to stop?" is a hard one to answer. Hopefully, the desired depth to just replace the SMD would occur simultaneously near the upper and lower ends. However, it could be either one. Unfortunately, when this condition occurs, the water may not be far enough down the strip so it will have to run longer to irrigate the lower end. Or it may be too far down the strip, and be running off a lot. Again compromise is inevitable.

In addition to the problems illustrated, there are obviously many more combinations of the controllable items: stream size, MAD, time and distance to cut-off and length, to which should be added return flow systems.

The diagnosis of conditions is obviously rather complicated. Some assistance can be obtained from trained people. Cal Poly State University, San Luis Obispo, agricultural engineering students and graduates, and some others have studied evaluations and they can be helpful. Several engineering and farm management firms have adequate staff. The Soil Conservation Service and Farm Advisors' Offices have some experienced personnel. For the tremendous job of efficiently using a short water supply, most irrigators will have to depend on themselves. Hopefully this booklet will be of assistance.

The value of water is not its cost, nor the labor to apply it. It is measured by what the water and labor will produce when water is in short supply.

Chapter IV

MANAGING THE SPRINKLE METHOD

Sprinkle (and trickle) irrigation method is unique in contrast to surface methods in that it is independent of soil uniformity and topography in its adaptability. It is also compatible to a small steady stream of water when surface irrigation works best with large flows. However, disregarding adaptability and contrary to popular opinion, sprinkle has the lowest potential efficiency of any normal irrigation method. Also, it is difficult to modify for drought conditions.

The basic reason for the good reputation it does have is that most systems are fairly well designed and the design efficiency is presumed to be the operating efficiency. However, in general, the pre-nozzle losses are ignored and the coefficient of uniformity is frequently incorrectly thought of as being the efficiency of the method.

This chapter will present the management procedures to identify and alleviate its losses in order to increase efficiency up to the fairly good values that are attainable. A number of factors will be presented that apply to sprinklers in general, and then the unique conditions will be covered for the following specific variants of the method: single line (hand move, side roll, end tow), multi-line system (permanent, solid set, side roll with trailing laterals), and orchard (over-tree, under-tree, permanent, portable).

Some of the techniques may be fairly expensive or labor intensive, but in a water deficient period the value of water is in its productivity. If an efficiency of 60% can be raised to 75%, twenty-five percent more land may be planted and irrigated with the same water supply. This increased yield can justify a very appreciable expense.

The two basic questions "Is it dry enough to irrigate?" and "Is it wet enough to stop?" must be answered. For most sprinkle systems the implied correct answer for frequency and duration at the time of peak water demand is designed into them. This usually results in 12- or 24-hour sets less changing time. Almost all systems are operated in conformance with this design duration for the convenience of labor. If the existing Soil Moisture Deficiency (SMD) in the field at the day of irrigation is equal to the Management Allowed Deficiency (MAD) for which the system was designed, fairly good efficiency should result. Not very much will go too deep below the MAD line as illustrated in Figure 6.

SPRINKLE IRRIGATION

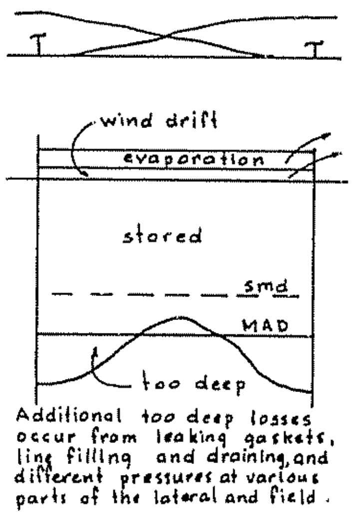


FIGURE 6

However, if the designed peak frequency and duration are used and the SMD does not equal the desired MAD as is also shown on the figure, serious loss of water to too deep will occur since everything below the SMD line now goes too deep. For example, if a 20-hour set would replace the SMD, but the run is 24-hours (24-20/20) = 20% water is lost in addition to the regular losses.

It is essential that the operating frequency or duration be made to conform to that needed to replace the SMD existing at the day of irrigation. This will often require an inconvenient duration of operation, but water run too long is 100% wasted. There is no return flow to save water with sprinklers. Not properly answering the second question is the principle reason the sprinkle Actual Application Efficiency (AAE) seldom equals the Potential Application Efficiency (PAE).

Another loss that puts water too deep is caused by the non-uniformity of the sprinkler application pattern. Most individual sprinklers at their best operating pressure, put out much water close to the sprinkler and taper out to zero at the edge. This results in a somewhat conical shaped pattern. By overlapping one sprinkler well past the next along the line, a long triangular tent-like pattern results. This is then moved sideways to nearly reach the next line to overlap the tent-like patterns.

With the right combination of nozzle size, pressure, sprinkler spacing along the lateral, and distance between laterals, a reasonably uniform overall pattern results from the many individual conical patterns. However since nozzle size and pressure are often compromised in the design to apply the desired depth in a 12- or 24-hour duration, the best pattern is seldom attained. Modifications to help will be discussed later.

A field evaluation (in which catch cans are set out and depth measured as described in the booklet, Irrigation System Evaluation and Improvement) is essential to determine the distribution uniformity coefficient (DU). (DU = average depth infiltrated in the quarter of the area receiving the lowest depth/average depth infiltrated). The value of DU for good operations will range from 75% to 85%. This indicates the too deep loss is from 15% to 25% of that infiltrated when the flow is shut off on time. (Those values correspond to the commonly used coefficient of uniformity values of about 83% to 90%.)

The pattern is also distorted by wind. This is alleviated by using a lower pressure to create fewer small drops which are more affected by wind. Laterals should not be placed parallel to the wind, 45^{o} to 90^{o} being less distorted. Avoidance of windy periods is the best control, and 24-hour sets are better than 12-hour ones. Where practical, the use of alternate sets described later is very helpful as is also closer spacings along and between the lateral. The decrease in DU varies from 2 or 3% to perhaps 6% for fairly high winds.

Other too deep losses (which are not included in the PAE evaluation figures which are measured at the sprinkler nozzle) also occur. These losses need to be included in the field efficiency as water to satisfy them must be delivered to the field. These losses are leakage from poor gaskets, losses occuring while filling the lines and before pressure seals the gaskets, and the water lost while draining the laterals. They amount to from 2% to 7%. Good maintenance can reduce the higher values.

Another loss of a similar nature is that caused by having different pressure along the lateral caused by friction and differences in elevation, although the latter can also be helpful if downhill. The usual design limit of a 20% reduction in pressure along a lateral results in 10% more water flowing from the first sprinklers than from the last. If the flow from the sprinklers at the lower end is what is desired, about 3% excess water will be applied along the upper part of the lateral.

This can be alleviated by using flow regulating devices in the risers or a larger diameter lateral with less than 20% friction loss. The latter will reduce pumping costs.

However there is a complication due to the 20% pressure change in that there is an effect on the pattern. The DU at the various places along the lateral will be different. One cannot offhand tell whether the lower flow and pressure at the lower end might not also coincide with a less desirable DU. Field evaluations are definitely in order.

To summarize the too deep losses: the system may be run for an incorrect duration which is correctable, the pattern DU may be poor and corrections will be discussed under each type, line losses occur which may be reducible with good maintenance, and flow and pressure variations along laterals may be helped by installing flow regulating devices or having less pressure loss or more consideration for ground slope.

The in-air losses are unique to the sprinkler method. They are included in the PAE and AAE values since they occur after the water leaves the nozzle. The evaporation loss is related to the relative humidity and will be affected some by temperature, wind, and sprinkler layout, by water temperatures, and somewhat by drop size. The latter is a function of pressure and nozzle diameter.

This loss varies from about 5% to 15% and even higher under severe conditions. The in-air evaporation is less at night when it is cooler and the relative humidity is higher. However during the daytime water on the plant leaves effectively stops plant transpiration so that water normally removed from the soil remains there. The net effect is that there is usually only a small difference whether water is applied during the day or night unless severe climate conditions prevail. If they do, sprinklers may become impractical particularly with saline water. A 20% evaporation increases water salinity by 25%.

Where multi-line systems (solid set, etc.) are used, evaporation will be reduced except for the up-wind lines.

Wind drift losses are only a few percent for normal pressures and moderate winds though the pattern will be affected. For extreme conditions of high pressure with fine drops and appreciable wind, it may be as high as 5%. Multi-line operation may recover part of the drift. Lower pressure and avoidance of very windy periods are obvious ways to reduce the loss. They may have side consequences -- less water, larger drops, longer duration -- that makes these changes impractical, so management compromises.

Another general problem with sprinklers occurs along the edges of the fields. Since there is no lateral line set beyond the edge, only one line of sprinklers lacking the usual overlap applies water there. In order to get a fair amount of water - but usually a deficient amount - the lateral in a typical operation is set fairly close to the edge and water is thrown outside the field. This can be overcome in some systems by tipping the risers so that the water hits the ground at about half the move distance or less from the lateral. This will concentrate the over-thrown water in close and make the application quite uniform. The impact of the jet may damage some crops and will certainly pack bare soil. The end sprinklers or the laterals may have their risers permanently bent a little.

If, by utilizing some of the various ways to improve efficiency, the value of the PAE of the system is improved, the duration of operation must be correspondingly reduced. This probably will be to some inconvenient duration in order to infiltrate the same minimum depth as before, or a larger MAD must be used. If this is not done, AAE will not increase and more water than before will be lost to too deep.

When water supplies are decreased from regular sources or because of falling water tables in wells, all of the available land may not be planted even with increased efficiency. If laterals are shortened so that unplanted land is left at the far edge of the field, the flow in the lateral will be correspondingly reduced. Less pressure will be needed to overcome friction without affecting the sprinkler pressure, so power may be saved. If a 1320 foot lateral were reduced to 990 feet, the pressure could be reduced from say 65 psi to 56 psi for about 15% reduction in power. It would also provide more uniform sprinkler flows along the lateral and save a little water. To save power, the pump impeller would need to be changed which is a fairly inexpensive job. Throttling the inlet valve will not save much power.

If throttling is currently being done, a review of the pump is in order to see if changes can be made. For constant speed pump, a 10% reduction in impeller diameter results in a 10% decrease in flow, reduces pressure 20%, and horse power by 30%.

For the single line sprinklers - hand move, side roll, end tow - the total area and the set area may be decreased by reducing the lateral move distance. This usually increases the DU and application rate which will reduce the time of irrigation or result in more water being applied at the low quarter area. It therefore may be practical to reduce the flow rate and pressure saving water and energy. Renozzling may sometimes be desirable. The new condition would require a field evaluation to determine the new DU.

Another practice that should be standard with the single line system because it almost invariably improves DU by 5 to 15%, is the use of "alternate sets." In this practice the regular move distance and frequency are used each time, but at alternate irrigations the starting location for the lateral is midway between the previous sets. The high application area of the first set tends to compensate for the low application of the alternate sets. A minor edge problem occurs due to the need to compromise the distance in from the edge of the field at the start. And again duration or other changes must be made because of increases in efficiency. A wider than normal move distance often becomes very acceptable with alternate set utilization. The improved efficiencies again require a reconsideration of the duration of the set.

The multi-line systems -- permanent, solid set, side roll with trailing laterals -- are less amenable to modification. Changes of spacings are not feasible for permanent laterals and solid set, so the alternate set techniques cannot be used. Closer spacings usually resulting in higher uniformity may be easily done with solid sets when first laid out. Risers along the edges may be tilted for some crops.

Modifications that may be practical include changing pressure and related flow rate and probably DU, varying pressure at alternate runs, and operating for the correct duration and then shutting down or starting the next block is essential.

Evaluations are important for solid sets and permanent lines since, for economics which is good design except in drought, pressure variations may be rather large. Smaller nozzles to reduce flows to obtain more uniform pressures and possibly a lower one, may be helpful. This will change duration but on automated systems this poses no great problem. It may also be necessary to add or subtract one line in the block to balance flows with the pump, and also the frequency of coverage. Remember, less water and time is needed with better efficiencies.

Orchards and vineyards have several variations of sprinklers. A common one is permanent over-tree. These lack adjustability and their pattern cannot be evaluated. It is often poor at the ground level due to plant interferences. Use of a probe to check depth of penetration in many areas may be helpful. If over-irrigation is not very great, the extensive root system will absorb water wherever it is, but there will be dry areas develop during the middle or latter part of the season. About the only management tool is to avoid over-irrigation and possibly operate at different pressures at different irrigations to vary the pattern.

The open field type sprinklers requiring overlap for uniformity have been used as permanent or portable under-tree sprinklers. They are sometimes facetiously known as "through-the-tree" sprinklers. If there is much tree interference, and there usually is, resulting in excessively wet and dry areas, the uniformity can be quite poor often resulting in ponding and runoff. If they are portable, the alternate set technique may be helpful.

The under-tree sprinkler, properly known as an "orchard" head, should cover the area between four trees with a uniform depth pattern not dependent on overlap from adjacent sprinklers. They usually operate at fairly low pressure. Such a setup can be permanent or portable. Several water saving and management practices are helpful in drought years to maintain production with a reduced water supply.

Most of these heads are adjustable, and while adjusting them may be a formidable job, improved quality and yield have great value. They should be adjusted to produce as uniform a pattern as practical, especially avoiding areas of excessive precipitation which could be lost to too deep. The duration of flow should be such that all but perhaps the last one or two irrigations should penetrate nearly to the bottom of the root zone. Some may be shallower to save storage for rainfall.

In order that about this depth, never more and possibly a little less, is attained, the area wetted may need reducing by adjusting the range and/or pressure. To summarize - wet only as much area as water is available to penetrate the root zone. Do not put on shallow, large area irrigations, but do force the tree to ration itself by using large MAD values and the deep roots. Efficiency above 85% is attainable.

To summarize sprinklers: they are widely adaptable to intermixed soils and unlevel topography. They have more built-in losses, before and after the nozzle, than other methods. They are easily misused, particularly by running too long for an existing SMD. They have limited capability for improvement as a system because they generally are fairly well designed. Management changes in some cases need to be based on a field evaluation. Such changes to improve uniformity may include: varying the spacing and move distance of the sprinkler and using the alternate set technique; varying pressure, flow rate, and nozzle sizes; and tilting risers along the edges of fields. Additional important techniques include varying the MAD and corresponding duration of flow, and, above all, turning off the flow when the SMD has just been satisfied, or shortly before for drought operation.

Under-tree orchard heads can be adjusted to improve uniformity, and to balance the area wetted with a reduced water supply to permit penetration to nearly the full depth of the root zone with negligible too deep loss.

Several procedures may involve a change in the pump. The latter may be as simple as using a smaller impeller.

Chapter V

MISCELLANEOUS MANAGEMENT METHODS

The preceding chapters have presented the value and need for efficient irrigation, particularly during the water deficient periods, and also how to operate furrow, border-strip, and sprinkler systems to attain high efficiency. Certain management techniques in addition to operations need further development beyond that previously presented. They will be covered under the three often mentioned phrases: "Is it dry enough to irrigate?" "Is it wet enough to stop?" and "Losses," and the common closing heading of "Miscellaneous."

"Is it dry enough?" requires two "yardsticks" -- Management Allowed Deficiency (MAD) and Soil Moisture Deficiency (SMD). MAD is first expressed as the percent of the available moisture in the root zone that can desirably be used and correlates with the stress that will occur in the crop in the specific soil and climate condition. This percent is often taken as 50%, but desirably should often be 40% to 80% depending on conditions.

When one has selected the MAD percent and knows the available moisture relations for his soil and depth of root zone, he can multiply them and determine what inches of soil moisture can desirably be removed from the soil (MAD inches) at the time to irrigate. The irrigator should replace the deficient inches depth comparable to the same inches of rain.

For example, a 60% MAD may be the desirable value to moderately stress a crop in a medium textured soil. If the root zone is 5.0' and the available water in the soil between field capacity and wilting point is 1.8" per foot, the value of MAD = 60% (5.0' x 1.8"/') = 5.4". In other words that is how dry management says it should be at the time of irrigation so a rainfall of 5.4" should be prayed for, or that much plus the losses should be obtained from a more likely source.

The second "yardstick" is how dry is it in the root zone. What actually is the Soil Moisture Deficiency? Does it equal the MAD? This is determined many ways. A common one is by intuition which occasionally may be close but most often is used with too much "worry factor" and results in much wastage of water.

Observation of crops for signs of incipient stress, slight wilting, color change, slower growth, etc., can be quite practical in selecting a date for irrigation. However, it does not indicate what the SMD is so does not furnish knowledge of how much water is needed.

Other techniques that indirectly tell that it is time to irrigate include the use of tensiometers, electrical resistance blocks, evaporation pans, calculated evap-transpiration, neutron probe, etc. These must be calibrated with field conditions to estimate the SMD and when and how much water should be replaced.

A simple, less expensive, more direct, more informative, and -- with some personal experience -- as precise a method is the observing of the actual soil moisture deficiency in the field. The chart (Figure 7 in the Appendix) describes the feel and appearance of the various textures when they are deficient the indicated amounts per foot of soil profile. The irrigator should replace the observed deficiency. It should be the same as the MAD at the date of irrigation. In any event, don't put on more, and not less, unless a limited irrigation is desired.

The following is an illustration of the use of the chart. A soil auger* or sample tube is used to obtain samples of each foot of profile. If the top foot condition matches the description of the soil (texture, feel, appearance) indicating a loam soil, 1.8"/' deficient (wilting point), second foot 1.0"/' deficient, third foot .4"/' deficient, and fourth foot 0.0"/' (field capacity), the soil is deficient the sum of these, 3.2", and the root zone depth is about three feet. The irrigator should apply 3.2" of water plus that needed to satisfy the losses. He should check the soil at several locations. Don't complain about the work, because you can hire irrigation management service (IMS) companies to do it, but it is essential that the question be answered.

Another simple guide can be used to tell about when to make a check. It can even be refined to schedule when to irrigate, but it must be confirmed every couple of irrigations by a soil moisture deficiency check. This is a gallon can nearly full of water set out in the sun. Before the MAD depth has evaporated, make a field check. By varying the initial depth of water in the can, the evaporation rate can be varied to approximate the evapo-transpiration rate of different crops.

The selection of the MAD value involves many factors. (A copy of the American Society of Agricultural Engineers technical paper describing this may be obtained from the Agricultural Engineering Dept., California Polytechnic State University, San Luis Obispo, CA 93407.) A value of 50% correlates with the top part of the root zone being dry (wilting point) and of course the bottom being wet (field capacity). For the most efficient production of crops per unit of water, the crop should be stressed and values of 60% to 80% may be

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* An excellent soil auger can be obtained from Art's Machine Shop, Harrison St. at Oregon Trail, American Falls, ID 83211

economical. The following tables indicate the MAD, water use, and yield relations from tests made at Prosser, Washington, for corn and sugar beets. There is also a significant saving in labor with the larger MAD values.

CORN

MAD %	No. of Irri.	Yield bu./ac.	Water used	Yield bu./in
40 (wet)	9	128	33.2"	3.9
65	4	118	25.3"	4.7
85 (dry)	3	110	23.6"	4.9

SUGAR BEETS

MAD %	No. of Irri.	Yield ton/ac.	Water used	Yield ton/in
40 (wet)	12	37	46.2"	0.80
65	8	36	37.3"	0.98
85 (dry)	6	34	32.0"	1.05

These tables indicate more land can be planted with a limited water supply and a larger total production obtained though at a lower rate per acre, if a larger MAD is used.

The second question "Is it wet enough to stop?" can be answered in several ways. The most simple is to use a steel rod 3/8" or 5/16" in diameter about 4.0' long with a tee handle. The end of the probe is left square across. It is not pointed since it is used while irrigating to feel the change in resistance to being pushed through the ground between the nearly saturated soil being wetted and the drier soil below. When used in sticky soils, the lower tip should be slightly enlarged so the soil won't stick to the side. This permits the tip to be more sensitive to changes in resistance.

The probe is used during irrigation. It can be used to quickly make many tests in many areas of the field. Since the water will continue to move downward in the soil for a couple of days after irrigation, the depth of water and probe penetration should be about half way down into the root zone when the water is turned off.

To develop confidence in its use, a soil moisture check should be made with an auger a couple of days later to see just where water did penetrate. If not enough was applied, a slightly drier (but still quite wet) condition should show up at the bottom. If too much was applied, it will be wet all the way indicating some unknown excess was applied. When water is deficient or expensive, under-irrigation is economical.

A second way to stop irrigation is to run out of water. In other words, order or pump an amount that equals the SMD plus losses, and no more. This amount (depth on the field plus losses) can be calculated. It is equal to the flow rate (cubic feet per second, cfs; gallons per minute, gpm; miner inches, M.I.) multiplied by the time water was running onto the field. Either of two equations is commonly used. The first is:

cfs x T hours = acres x inches depth which is conveniently expressed and easily remembered as 1.0 cfs x 1.0 hour = 1.0 ac x 1.0 inch deep.

For example, how long should a stream of 5.0 cfs be run on an 8.0 ac field to satisfy a 3.5" SMD at 70% efficiency? To allow for losses, one needs to apply 3.5" ÷ 70% = 5.0", then 5.0 cfs x T hours = 8.0 ac x 5.0". The duration of flow is 8.0 hours. Of course this time must permit just the desired depth to infiltrate. Usually the duration, depth, and flow rate are known and the question is how many acres can be irrigated.

Gallons per minute can be converted to cubic feet per second by this ratio: 450 gpm = 1.0 cfs. Also, 50 Southern California miner inches = 1.0 cfs, and 40 Northern California miner inches = 1.0 cfs.

The second convenient formula is: Depth (inches) = Time (hours) x 96.3 x gpm/area (square feet).

Losses can be alleviated by several management practices in addition to the too deep and runoff losses written about in the preceding chapters.

Transpiration Irrigation Ratio (TIR) (the percent of the water applied that is transpired by the crop) can be improved by reducing the losses to evaporation. The direct losses from the water while it is being applied are not reducible in a practical way for any of the methods.

However, the evaporation from the ground surface after irrigation -- which may amount to .3" to .8" each irrigation -- can be limited in several ways: shading the wet ground by growing a crop or mulching; reducing the area wetted by irrigation by use of furrows, or orchard sprinkler heads wetting only part of the area; reducing the frequency of irrigation by using a larger MAD; not cultivating unless weeds are being competitive with the crop; etc.

Alternate side irrigation of row crops or orchards should almost always be a standard procedure because of several advantages. The practice consists of first irrigating one side of the plant (every other row) which will require only half of the normal stream and permit a smaller capacity supply system. Then at half of the normal irrigation frequency, irrigating the other side.

For many fields this will require very little more work and usually no more total labor time. The advantage to the crop results from one side of the crop always being fairly wet. This may permit larger MAD values which allow longer runs, more efficient irrigation, longer intervals between irrigation, and so less labor. It also provides a dry area in the field for easy access.

Return flow systems, which recover run off water from surface irrigation systems and should almost always be utilized, have three general ways to function. The runoff water can be accumulated in a fairly large (several acre feet) reservoir (sump) at the bottom and pumped out using a fairly large pump and pipeline for direct inflexible use on a field at a convenient time.

Or a smaller sump, and a fairly large pump and pipeline can be used. Pumping is started after runoff has practically filled the sump, pumping both runoff and stored water. This generally involves more irrigation labor to distribute the water and may not be convenient in time.

The third consists of a small cycling pump, sump, and pipeline returning runoff as it occurs to a gravity irrigation storage reservoir from where it can be re-regulated for convenient use. This is the most desirable and generally the most economical.

For efficient use of water and labor, the on-farm distribution system should be semi-automated, be easy to use, and have a large enough capacity to keep the irrigator busy. It would ideally consist of a supply flexible in frequency, rate, and duration such as can be obtained from an overnight gravity storage reservoir. The delivery system from it must be capable of a delivery that is flexible in rate and duration, be of large capacity, and permit finger tip control at the point of application in the field.

This can be obtained from a reservoir by using a closed, or a semi-closed pipeline with a Harris float valve, or a level top ditch maintained full regardless of the rate of flow by an automatic control such as a Neyrpic constant downstream level control gate. Distribution from it for furrows can best be done utilizing small gated pipe reaching a short distance (100' to 150') each way from controlled outlets.

With such a layout with the control valve wide open, all regulation is at the individual gated pipe outlet to the furrow. However, after the individual outlets are set in a unit of gated pipe, the starting, cutting back, and turning off is done at the individual controlled outlet from the supply system.

For border-strips, the controlled outlets can place water directly into the strips at any rate and number up to the capacity of the system which should be large.

This type of a system is considered as semi-automated because it is manually operated at the point of distribution, but variations in rate from the reservoir require no work on the part of the irrigator since the closed pipeline or float valves in the pipeline or level top ditch eliminate the need. Large streams of water can be handled with very little labor at high efficiencies with this type of distribution system.

By choosing the best adapted method and operating it correctly, by checking the soil moisture deficiency and comparing it to the Management Allowed Deficiency to determine when to irrigate, and then by turning the water off when enough has been infiltrated, one can obtain very efficient irrigation.

By having a system with a large enough capacity to keep an irrigator economically busy, and one that is easy to use, labor costs can be kept low.

If one has these things one can have efficient irrigation and plant more land with less water.

APPENDIX

Glossary

Management Allowed Deficiency (MAD) is the soil moisture deficiency in the root zone at which management anticipates the economically optimum condition. It is first expressed as a percent of the available moisture in the root zone corresponding to the desired maximum stress in the plant. It is then converted to the corresponding inches of soil moisture deficiency in the root zone which is the desired depth of water to be applied.

Soil Moisture Deficiency (SMD) is the depth of moisture (dryness) that has been removed from the root zone at any particular moment. It is the maximum that can be replaced and stored in the root zone. It can also be expressed as the deficiency in a unit depth of soil, e.g., inches deficient/foot of soil.

Time of Irrigation (T_i) is the duration that is needed to infiltrate the desired depth of water at a point.

Time of Application (T_a) is the duration that water is being applied to the field.

Time of Advance (T_{adv}) is the duration needed for the stream to move across the field.

Time of Opportunity (T_o) is how long water was on the surface with opportunity to infiltrate the soil.

Time of Lag (T_L) is how long the water remains at the upper end of a field after it has been turned off.

Advance Ratio (AR) is the ratio of the Time of Advance to the Time of Opportunity at the far end of a furrow or field and which ideally is T_i.

Cumulative Depth Infiltrated Curve is a plotting of the depth of water that entered the soil after any increment of time. It usually plots a straight line on logarithmic paper.

Depth Infiltrated Curve is a plotting of the depth of water that has penetrated the soil at various places across a field, or an extension of it.

Advance Curve is a plotting of when the moving water arrives at various places across a field, or an extension of it.

Recession Curve is a plotting of when water disappears from various places across a field, or an extension of it. The time difference between it and the Advance Curve is the duration (Time of Opportunity) that water is at any point.

Irrigation Curve is a plotting of when water should disappear from various places across a field. It is plotted parallel to the Advance Curve and above it by the Time of Irrigation.

(In the following three equations, the minimum depth is the average depth in the quarter of the area receiving the lowest amount. ie. about one eighth of the area is slightly under-irrigated.)

Potential Application Efficiency (PAE) is the ratio of the minimum depth of water stored when that just equals the soil moisture deficiency (SMD) to the average depth of water applied. It is the measure of how well the system can do the job.

$$PAE = \frac{\text{min. depth stored} = \text{SMD}}{\text{av. depth applied when the SMD is just satisfied}}$$

Actual Application Efficiency (AAE) is the ratio of the minimum depth of water stored to the average depth of water applied. The minimum depth stored cannot exceed the SMD but may be less. It is a measure of how well a system is being used.

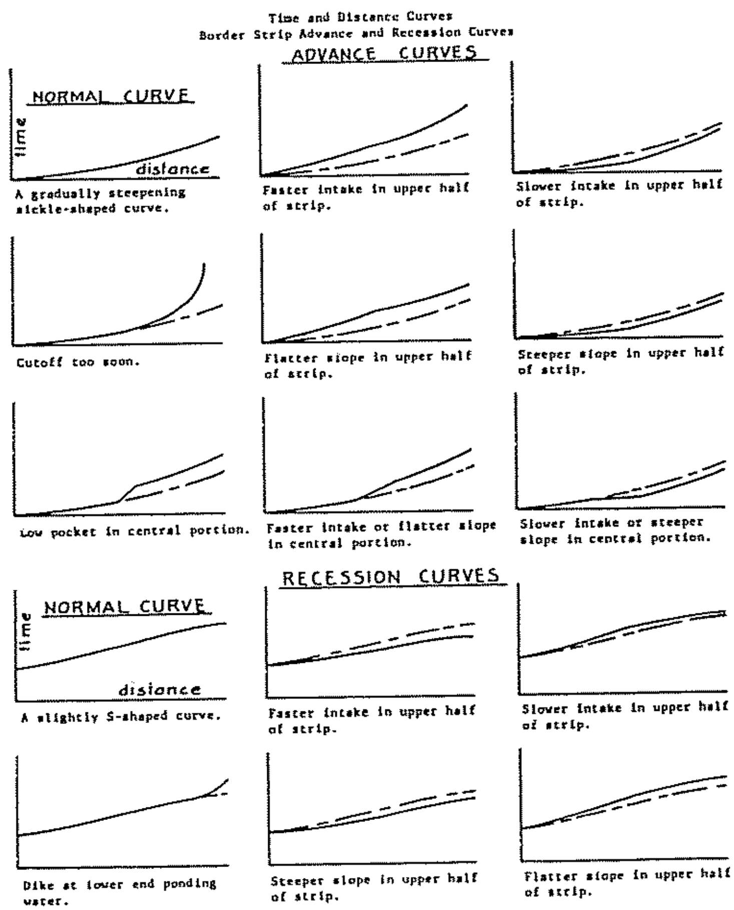
$$AAE = \frac{\text{min. depth stored}}{\text{av. depth applied}}$$

Distribution Uniformity (DU) is the ratio of the minimum depth of water infiltrated to the average depth of water infiltrated.

Minimum Depth is the average of the one fourth of the total area that receives the least water. Approximately one eighth of the total area will receive from zero to slightly less than this minimum value.

Coefficient of Uniformity (C_u) is the ratio of the average depth infiltrated minus the average deviation from this average depth (or caught in sprinkler tests) to the average depth.

$$C_u = \frac{\text{av. depth infiltrated - av. deviation}}{\text{av. depth infiltrated}}$$


Time and Distance Curves
Border Strip Advance and Recession Curves
ADVANCE CURVES
NORMAL CURVE
time
distance
A gradually steepening sickle-shaped curve.
Faster intake in upper half of strip.
Slower intake in upper half of strip.
Cutoff too soon.
Flatter slope in upper half of strip.
Steeper slope in upper half of strip.
Low pocket in central portion.
Faster intake or flatter slope in central portion.
Slower intake or steeper slope in central portion.
RECESSION CURVES
NORMAL CURVE
time
distance
A slightly S-shaped curve.
Faster intake in upper half of strip.
Slower intake in upper half of strip.
Dike at lower end ponding water.
Steeper slope in upper half of strip.
Flatter slope in upper half of strip.

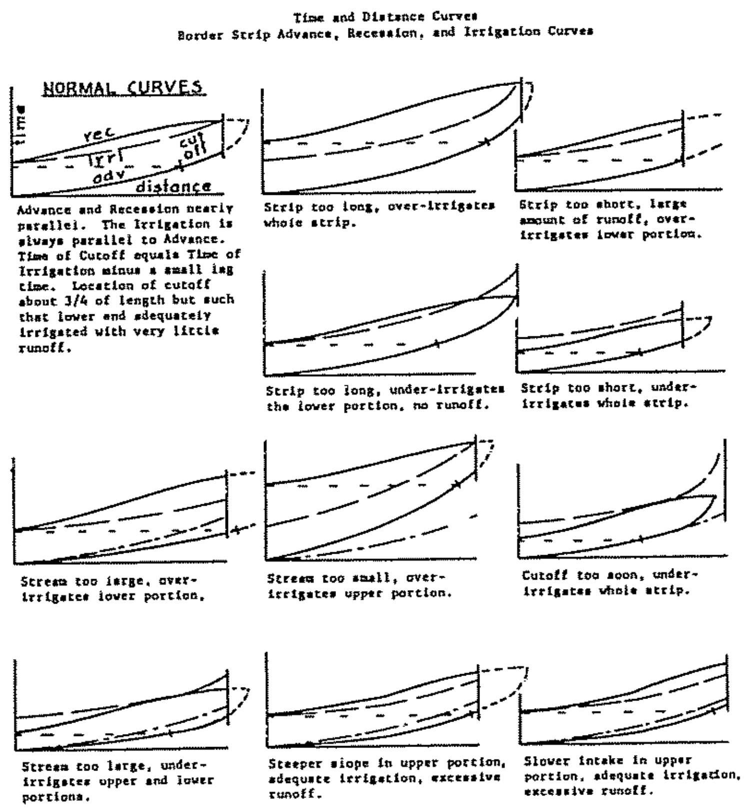

Time and Distance Curves
Border Strip Advance, Recession, and Irrigation Curves
NORMAL CURVES
time
rec
irr
adv
cut off
distance
Advance and Recession nearly parallel. The Irrigation is always parallel to Advance. Time of Cutoff equals Time of Irrigation minus a small lag time. Location of cutoff about 3/4 of length but such that lower end adequately irrigated with very little runoff.
Strip too long, over-irrigates whole strip.
Strip too short, large amount of runoff, over-irrigates lower portion.
Strip too long, under-irrigates the lower portion, no runoff.
Strip too short, under-irrigates whole strip.
Stream too large, over-irrigates lower portion.
Stream too small, over-irrigates upper portion.
Cutoff too soon, under-irrigates whole strip.
Stream too large, under-irrigates upper and lower portions.
Steeper slope in upper portion, adequate irrigation, excessive runoff.
Slower intake in upper portion, adequate irrigation, excessive runoff.

Figure 8

Figure 7

SOIL MOISTURE DEFICIENCY AND APPEARANCE RELATIONSHIP CHART

This chart indicates approximate relationship of soil moisture deficiency between field capacity and wilting point. For more accurate information the soil must be checked by drying samples.

Moisture Deficiency in./ft.	SOIL TEXTURE CLASSIFICATION Coarse (loamy sand)	Sandy (sandy loam)	Medium (loam)	Fine (clay loam)	Moisture Deficiency in./ft.
.0	(field capacity) Leaves wet outline on hand when squeezed.	(field capacity) Appears very dark, leaves wet outline on hand, makes a short ribbon.	(field capacity Appears very dark, leaves a wet outline on hand, will ribbon out about one inch.	(field capacity) Appears very dark, leaves slight moisture on hand when squeezed, will ribbon out about two inches.	.0
.2	Appears moist, makes a weak ball.	Quite dark color, makes a hard ball.	Dark color, forms a plastic ball, slicks when rubbed.		.2
.4	Appears slightly moist sticks together slightly.			Dark color, will slick and ribbons easily	.4
.6		Fairly dark color, makes a good ball.	Quite dark, forms a hard ball.	Quite dark, will make thick ribbon, may slick when rubbed.	.6
.8	Dry, loose, flows thru fingers. (wilting point)	Slightly dark color, makes a weak ball.	Fairly dark, forms a good ball.		.8
1.0		Lightly colored by moisture, will not ball.		Fairly dark, makes a good ball.	1.0
1.2		Very slight color due to moisture. (wilting point)	Slightly dark, forms weak ball.	Will ball, small clods will flatten out rather than crumble.	1.2
1.4			Lightly colored, small clods crumble fairly easily.	Slightly dark, clods crumble.	1.4
1.6			Slight color due to moisture, small clods are hard. (wilting point)		1.6
1.8				Some darkness due to unavailable moisture, clods are hard, cracked. (wilting point)	1.8
2.0					2.0

Field Method of Approximating Soil Moisture (Deficiency) for Irrigation; Transactions of the American Society of Agricultural Engineers, Vol. 3, No. 1, 1960; John L. Merriam, Professor, California Polytechnic State University, San Luis Obispo, California.

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Assessing irrigation/drainage/salinity management using spatially referenced salinity measurements

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Accepted 17 April 1997

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Abstract

A unique technology-package for measuring the spatial distributions of salinity in irrigated soils and fields and for evaluating the appropriateness of some related irrigation-, drainage- and salinity control-management practices is described. This assessment technology is based on the use of: (1) geophysical–instrumental systems for intensively measuring bulk soil electrical conductivity and associated spatial coordinates; (2) statistical algorithms for site selection and salinity calibration; and (3) algorithms for data analysis and graphical display to facilitate interpretation. Results are presented to demonstrate some of the utility of the technology. Additionally, examples are given which show that much of the apparent chaos observed in the spatial pattern of soil salinity in irrigated fields is man-induced and related to such management practices as irrigation, drainage, and tillage. © 1997 Elsevier Science B.V.

Keywords: Salinity; Irrigation; Drainage; Management; Assessment

1. Introduction

Irrigated agriculture accounts for a substantial proportion of our food and fiber production. Yet, extensive areas of irrigated land have been and are increasingly becoming degraded by salinization and water-logging resulting from over-irrigation and other forms of poor agricultural management (Ghassemi et al., 1995). In some places, sustainability of irrigated agriculture is threatened by this degradation. At the same time, irrigated agriculture is also depleting and polluting water supplies in many places.

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Increased irrigation efficiency is being sought to conserve water, to reduce drainage, water-logging and secondary salinization, and to mitigate some of the water pollution associated with irrigated agriculture. Restrictions are increasingly being placed on the discharge of saline drainage water from irrigation projects. Concomitantly, the reuse of saline drainage water for irrigation is being increased. With less leaching and drainage discharge and greater use of saline water for irrigation, soil salinity may increase in some areas. Thus, a practical methodology is needed for the timely assessment of soil salinity in irrigated fields, for determining its causes and for evaluating the appropriateness of related management practices.

Traditionally, soil salinity has been assessed using soil samples and laboratory analyses. Additionally, the leaching requirement (L_r) and salt-balance-index (SBI) have been used to judge the appropriateness of irrigation and drainage systems and practices with respect to salinity control, water use efficiency and irrigation sustainability (U.S. Salinity Laboratory Staff, 1954). However, these approaches are either inadequate or impractical for these purposes. Soil salinity is too variable and transient to be appraised using the numbers of samples that can be practically processed using conventional soil sampling and laboratory analysis procedures. Furthermore, the conventional procedures do not provide sufficient detailed spatial information to adequately characterize salinity conditions and to determine its natural or management-related causes. The leaching requirement (L_r), which refers to the amount of leaching required to prevent excessive loss in crop yield caused by salinity buildup within the rootzone from the irrigation water, is a 'concept' which traditionally has been used to evaluate the appropriateness of irrigation and leaching management. The concept is based on assumptions of steady-state and of absolutely uniform conditions of irrigation, infiltration, leaching and evapotranspiration; none of which are achieved in most field situations which typically are dynamic and variable, both spatially and temporally. Furthermore, salt buildup in the rootzone resulting from the presence of shallow water tables is ignored in the traditional L_r calculation. Additionally, no practical way has existed to directly measure the degree of leaching being achieved in a field, much less in the various parts of it, as is required in order to determine its appropriateness.

The salt-balance-index, the net difference between the amount of salt added to an irrigation project and that removed in its drainage effluent, is another 'concept' that has traditionally been used to evaluate the appropriateness of leaching, irrigation and drainage practices. This approach is also inadequate for these purposes because it provides no information about the average level of soil salinity in the project, nor about the soil salinity level existing within any specific field of the project. The approach also fails because it does not even provide a realistic measure of trends in salinity within the rootzone, because salt from below the soil profile and of geologic origin is typically contained in the drainage water collected by the subsurface drain system (Kaddah and Rhoades, 1976). Additionally, the transit times involved in the drainage returns are so long (usually more than 25 yrs) that the index values are not reflective of current trends (Jury, 1975a,b). Nor can one deduce the extent of leaching being achieved in any field, nor of the irrigation uniformity and efficiency, nor anything about the extent of waterlogging and losses in crop yield, because the SBI measurements are impractical to make on the basis of individual fields.

Our opinion is that an appropriate assessment of the adequacy of irrigation, drainage, water-table and salinity control management practices can not be achieved using L_r and SBI concepts. On the other hand, it is possible to measure soil salinity levels within the rootzone regions of individual fields. From these levels and distributions, one can determine whether they are within acceptable limits for crop production. One can also infer whether leaching is adequate and uniform, or not, anywhere in a field, since salinity is a tracer of the net processes of infiltration, leaching, evapotranspiration and drainage. Thus, a more appropriate and practical approach for assessing the adequacy of salinity control is the acquisition of periodic, detailed information of soil salinity levels and distributions within the individual fields of the project. We refer to this approach as salinity assessment and envision its use to diagnose, inventory and monitor conditions of soil salinity, as well as to evaluate the appropriateness of leaching and drainage and to guide management practices. The same data can also be used for delineating the sources of salt-loading, as well as for mapping the distribution and extent of drainage problem areas, within both the project and individual fields.

Control of soil salinity, and also of salinity in drainage-receiving water resources, requires the following: (1) knowledge of the magnitude, extent and distribution of rootzone soil salinity in the individual fields of the irrigation project (a suitable inventory of conditions); (2) knowledge of the changes and trends of soil salinity over time and the ability to determine the impact of management changes upon these conditions (a suitable monitoring program); (3) ways to identify the existence of salinity problems and their causes, both natural and management-induced (a suitable means of detecting and diagnosing problems and identifying their causes); (4) a means to evaluate the appropriateness of on-going irrigation and drainage systems and practices with respect to controlling soil salinity, conserving water and protecting water quality from excessive salinization (a suitable means of evaluating management practices); and (5) an ability to determine the areas where excessive deep percolation is occurring, i.e., to identify where the water and salt loading is coming from (a suitable means of determining areal sources of pollution).

An assessment technology of the type described above begins with a practical methodology for measuring soil salinity in the field. This is complicated by the spatially variable and dynamic nature of soil salinity, which is caused by the effects and interactions of varying edaphic factors (soil permeability, water table depth, salinity of perched groundwater, topography, soil parent material, geohydrology), by management induced processes (irrigation, drainage, tillage, cropping practices), as well as by climate-related factors (rainfall, amount and distribution, temperature, relative humidity, wind). When the need for repeated measurements and extensive sampling requirements are met, the expenditure of time and effort to characterize, map and monitor a field's or a project's salinity condition with conventional soil sampling and laboratory-analysis procedures becomes prohibitive. A more rapid, field-measurement technology is needed. Additionally, this assessment technology should ascertain the spatial relations existing within extensive areal data sets. It should provide a systematic strategy for evaluating management effects and be able to statistically prove changes or differences in an area's salinity condition over time.

The salinity assessment system described herein measures soil salinity in detail at the field scale and provides the information needed to accomplish successful management. It consists of mobile instrumental techniques for rapidly measuring bulk soil electrical conductivity (EC_a) directly in the field as a function of spatial position on the landscape, procedures and software for inferring salinity from EC_a, computer-assisted mapping techniques capable of associating and analyzing large spatial databases, and appropriate spatial statistics to infer salinity distributions in rootzones and changes in salinity over space and time. The remainder of this text briefly describes this assessment technology and illustrates its utility for evaluating irrigation, drainage and tillage management and for locating areal sources of over-irrigation.

2. Assessment equipment and examples of use

Two kinds of mobile instrumental systems have been developed for measuring soil salinity at the field scale: one uses four-electrode units to measure EC_a; the other uses an electromagnetic induction sensor, either solely or together with four-electrode units, to measure EC_a.

2.1. *The mobile four-electrode system*

In this system (see Fig. 1), the electrodes are combined into the 'heels' of tillage shanks and mounted on a hydraulically controlled tool-bar attached to a tractor via a

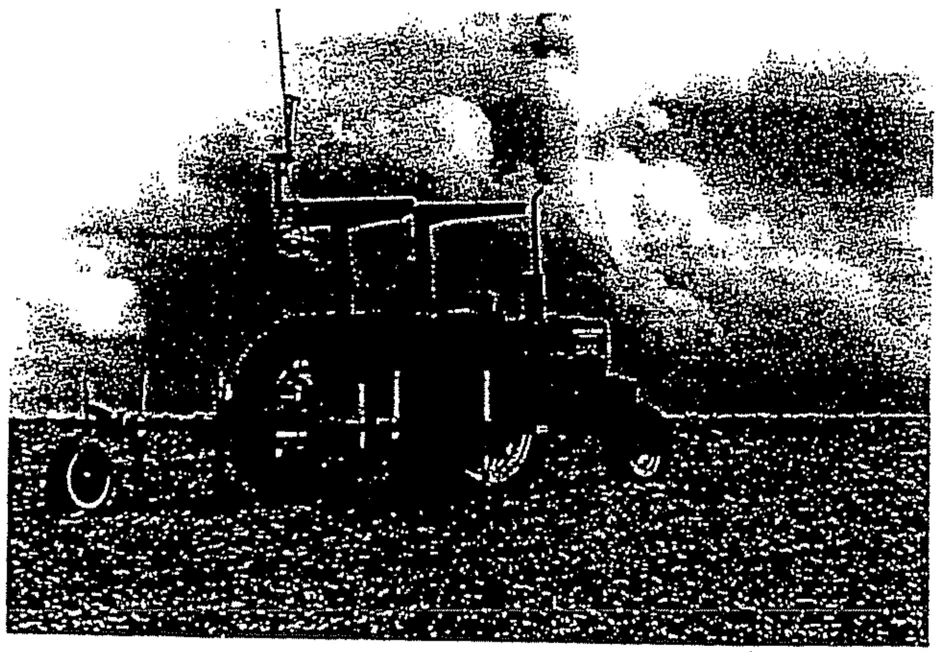

Fig. 1. Photograph of mobile, 'fixed-array' four-electrode system with GPS antenna mounted on the mast.

conventional three-point hitch. The distances between the electrodes are adjustable to accommodate different crop spacings. Typically, four row-spacings (about 3–4 m) are included in the measurement. The electrodes are drawn through the soil at a depth of about 10 cm as the tractor moves across the field at a speed of 1.0 to 2.5 m/s. A Global Positioning System (GPS) antenna is positioned above the electrodes and used along with a receiver to determine the spatial position of each sensor reading (the unit now being used is capable of real time accuracies of about 0.2 m). The EC_a and the GPS signals are sensed at adjustable frequencies (as often as every second) and logged into memory for later analysis of salinity/spatial relations. Thus, measurements of EC_a are made to a depth of up to 1.0 to 1.3 m (~ 4 row-spacings/3) about every 1 m or more, along the path of tractor travel. The four-electrode conductivity Martek meter used gives linear EC_a readings up to 15 dS/m. This corresponds to soil salinity values, as conventionally expressed in terms of the electrical conductivity of the extract of the saturated soil-paste (EC_e), of up to 45 to 100 dS/m, depending upon soil texture. The EC-meter, the GPS receiver, and their power supplies and data loggers are contained in the water-tight, stainless steel box mounted behind the tool-bar shown in Fig. 1. The tractor operator is provided with a remote monitor (not shown) displaying time, EC_a reading and logging status. The analysis of the spatial data is carried out at the side of the field in a mobile office equipped with a computer and with testing equipment for measuring the salinities (EC_e basis) of soil samples collected for purposes of sensor-calibration (explained later).

Example output data obtained with the above described mobile, four-electrode sensing system are presented in Fig. 2a, which shows EC_a readings collected every second (about every 1 m apart) as the tractor moved across a furrow irrigated, sugar beet field (Glenbar silty clay loam soil) in the Imperial Valley of California. Average rootzone soil salinities expressed in terms of EC_e, as predicted from the measured EC_a data along the transect and as measured in some 'calibration' samples, are shown in Fig. 2b. The theory and methods used to predict soil salinity from the sensor readings and limited calibration information, as well as 'fast', field methods for measuring EC_e, are described in detail elsewhere (Lesch et al., 1995a,b; Rhoades, 1992b, 1993; Rhoades et al., 1989a,b, 1990). As is shown here and in these earlier publications, the accuracy of these predictions is generally very good. The accuracies of the predictions are always quantitatively known from the statistical procedures used, though they are not shown here.

If irrigation application and infiltration were uniform across the field involved with Fig. 2, the value of EC_a (and EC_e) should be the same at each distance provided crop stand and soil type were also uniform. However in this case, the EC_a (and EC_e) values increased from the 'head' to the 'tail end' of the field; the coefficient of variability (CV) was 14.2% and the linear correlation coefficient (r) between EC_a and distance down the transect was 0.67. Thus, one may conclude from these rapidly (~ 6 min) obtained data that the field is not uniform with respect to one or more of the three possibilities. In this case, the crop was planted uniformly and the soil type was the same along the transect. Hence, the findings imply that irrigation application, or infiltration, was not uniform across this field, presumably due to reduced opportunity-time and infiltration of irrigation water with distance from the point of water delivery to the furrows. Another factor

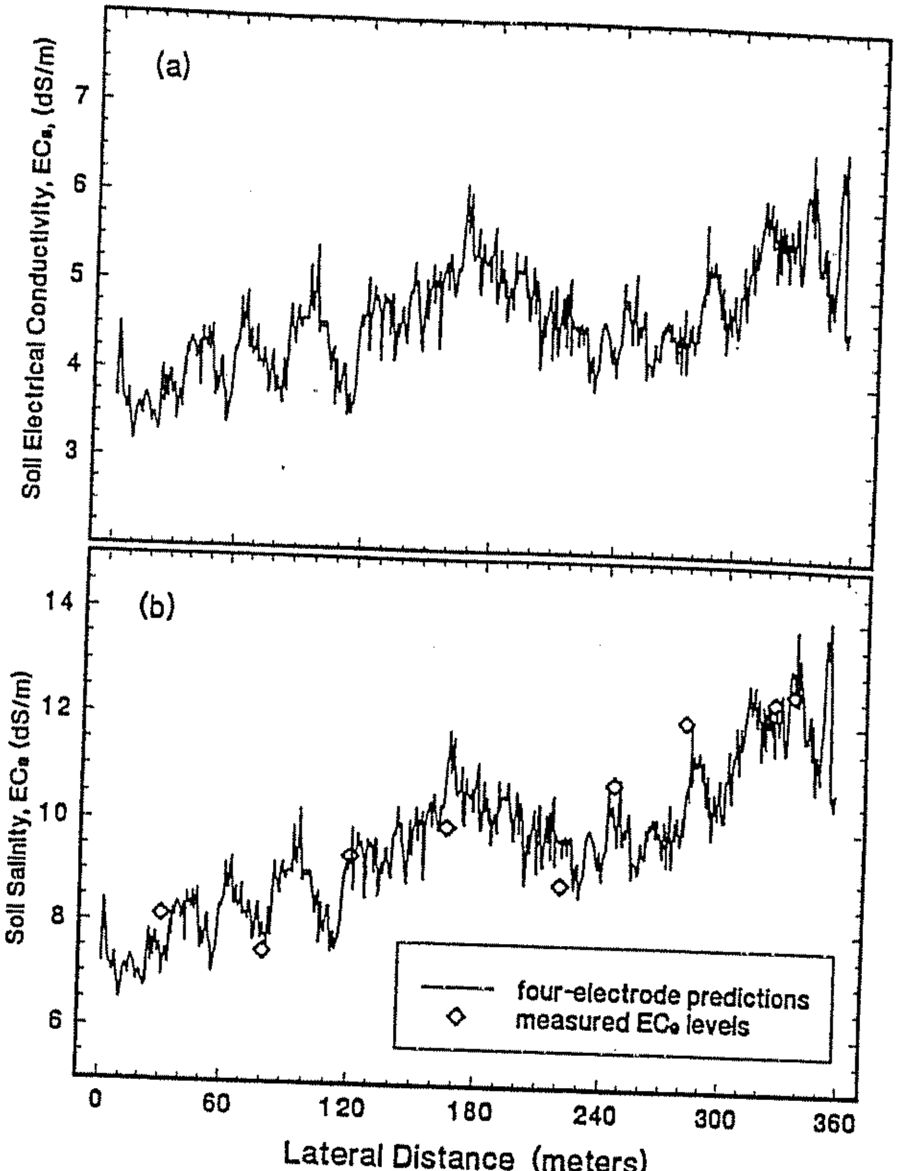

Fig. 2. Relation between (a) bulk soil electrical conductivity (EC_a) and (b) soil salinity (EC_e) and distance along a transect across a furrow-irrigated, sugar beet field (Glenbar silty clay loam soil) located in the Imperial Valley of California.

likely influencing the salinity distribution within this field is the lateral transport of salt that occurred in it as a consequence of the 'cracking' type of soil present in the field. This latter aspect is discussed elsewhere (Rhoades et al., 1997). This example illustrates how the spatial variation of average rootzone soil salinity can be used, assuming it is a tracer of the interactions of water infiltration, evapotranspiration, leaching and drainage,

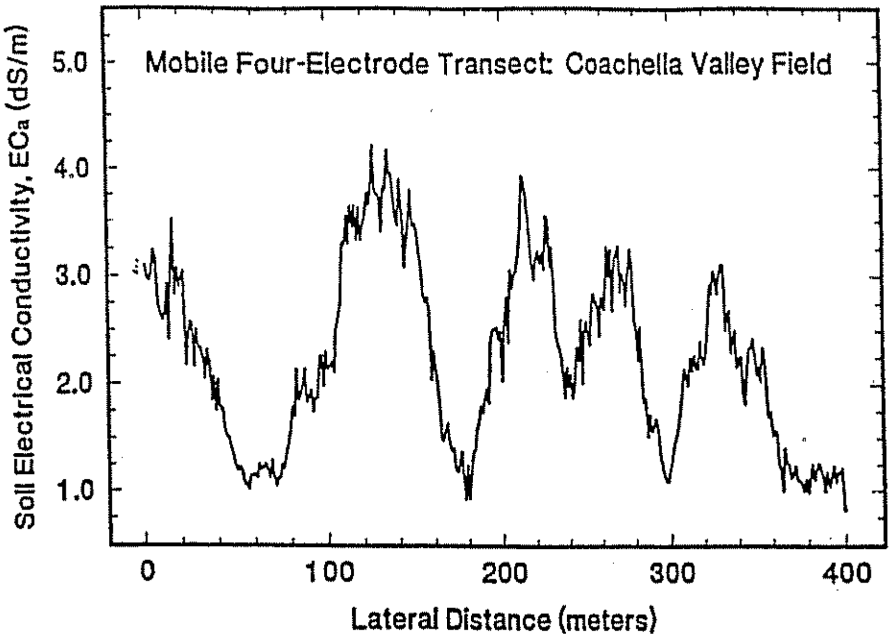

Fig. 3. Relation between bulk soil electrical conductivity (EC_a) and distance along a transect crossing subsurface tile-drains in field (silty clay loam soil) located in the Coachella Valley of California.

to evaluate irrigation uniformity in fields which are relatively uniform in soil type and cropping intensity.

An example of the marked effect that a subsurface drainage system can have on average rootzone salinity is provided in Fig. 3, in terms of EC_a. The corresponding values of EC_e (not shown) cycled between low values of about 2.5 dS/m to high values of about 25 dS/m. The CV and r values for this EC_a-distance traverse were 36.8% and −0.20, respectively. This example involved a field of silty loam soil in the Coachella Valley of California which had buried 'tile-lines' oriented perpendicular to the direction of the EC_a-traverse. In this field, soil salinity levels 'mimicked' the drainage system, with high values of EC_a (and EC_e) occurring in the soil located between tile-spacings and low values in the soil overlying them. These data suggest that most of the variability in average rootzone salinity across this field was caused by the effects of the drainage system. They also imply that the drainage system there was inadequate, given the circumstances of irrigation, soil type, geohydrology, etc. The distributions of salinity within the rootzone depth of such fields will be discussed later; they give further credence to the preceding conclusion.

The spatial pattern (average rootzone basis) of a neighboring field in the Coachella Valley determined using the above described equipment is shown in Fig. 4. The average profile EC_e value of 10–12 dS/m measured within the 0–1.2 m depth in much of this field is excessive for successful crop production. This observation itself is evidence of the inadequacy of the past irrigation and drainage management in the field. Assuming uniform irrigation and a leaching fraction of 0.05, the expected value of average

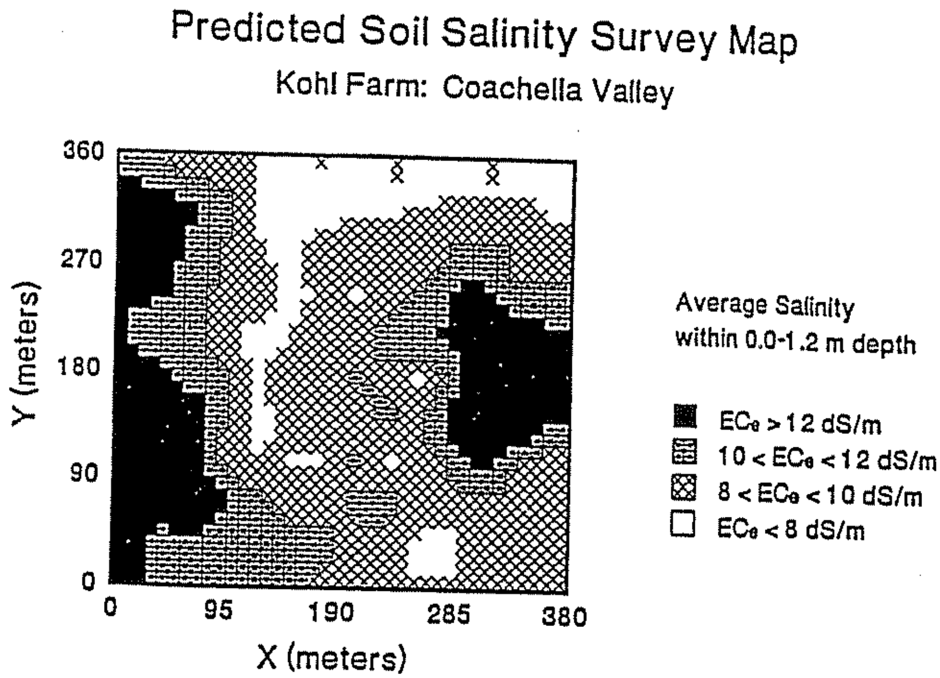

Fig. 4. Map of average rootzone (0–1.2 m) soil salinity (EC_e basis) in a tile-drained field (silty loam soil) located in the Coachella Valley of California.

rootzone salinity (as calculated using WATSUIT, Rhoades et al., 1992) would be about 2.1 dS/m under steady-state conditions of irrigation with the Colorado River water. Since the average soil-profile salinity in this field of silty–loam soil (non-cracking soil) exceeds 2.1 dS/m, one must conclude that the overall leaching fraction is negative either because of deficit-irrigation or because salt is being accumulated in the rootzone from the upflux of saline water from the water table. Since the information supplied by the irrigator showed that the applied water exceeded ET, the latter cause is deduced. The salinity distributions found within the profiles over much of this field are presented later; they also imply the cause is inadequate drainage.

2.2. *The combination, mobile electromagnetic-induction / four-electrode system*

This system involves a Geonics, EM-38 instrument mounted in front of the transport vehicle (a modified spot-spray tractor) within a vinyl ester pipe, as well as two-sets of four-electrode arrays (having 1- and 2-m spacings between current-electrodes, respectively) mounted underneath the vehicle, as shown in Fig. 5. The EM-38 mounting tube fastens to the vehicle by sliding over a short section of steel tubing. The 'EM-tube' is rotated, to enable the EM-38 readings to be made in both horizontal (EM_H) or vertical (EM_V) configurations, by means of a small gearhead DC motor and belt which operates via a non-slip cable applied to the tube. The tube and 'rotator' are mounted on a hydraulic apparatus which elevates the EM-38 sensor to various heights above ground

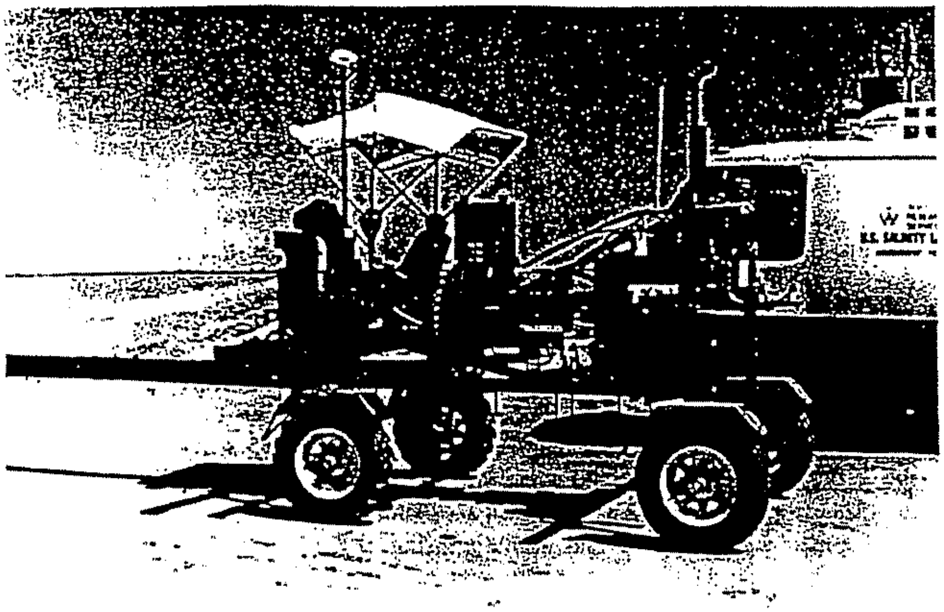

Fig. 5. Photograph of mobile salinity assessment vehicle with combined electromagnetic induction and four-electrode soil conductivity sensing systems.

and which also translates it in the horizontal direction, so as to allow both EM_H and EM_V measurements to be made sequentially at various heights above both the furrow and seedbed regions of the soil. The four-electrode arrays are mounted on a hydraulically operated scissor-action mechanism which includes a sensor and control mechanism to insert the probes sequentially to selected depths in the soil and also to correspondingly measure EC_a at both 1-m and 2-m array spacings in both the furrow and seedbed. These changes in the height and orientation of the EM sensor, in the spacings of the electrodes and in their positioning in relation to the furrow and seedbed are undertaken in order to alter the depths and distributions of the EC_a 'sensing' in the soil and rootzone and, thus, to permit the determination of the salinity-distribution within the rootzone in two dimensions (Rhoades, 1993). In Fig. 5, the EM-sensor and the four-electrode arrays are both in the 'up', or 'travel', position.

An automated control system was developed to carry out the sequence of 52 operations involved in the full range of possible sequential 'EM-38 and four-electrode' measurements. The control system is based upon switches and relay logic with auxiliary electronic timing. The control system is operated via an interface control panel with enable-buttons for activating the EM and four-electrode sensor measurements and for positioning the sensors over the furrow and seedbed in the case of the EM sensor and at various depths in the furrow and seedbed in the case of the four-electrode sensor. When the position-button is enabled, the EM sensor is rotated to the vertical (EM_V) configuration and the carriage moves both the EM and four-electrode sensors to the selected position (e.g., above the furrow or seedbed). The EM 'start' button then initiates the following automated sequence: (1) the EM_V reading is made and the reading is 'stored' in the data logger; (2) the EM-38 sensor is rotated to the horizontal position; (3) the EM_H reading is made and logged; and (4) the EM-38 sensor is rotated back to the vertical position. This sequence is repeated for each Y–Z position selected. Depressing the four-electrode 'start' button initiates the following automated sequence: (1) the scissors apparatus inserts the probes to the first depth limit, (2) EC_a is measured at the 1-m array spacing, (3) the 1-m reading is stored in the data logger, (4) the m/logger is switched to the 2-m array, (5) EC_a is read at the 2-m array spacing, (6) the 2-m reading is stored in the data logger, (7) the probes are inserted to the next depth limit (up to 5-depths are possible), and (8) steps (2)–(6) are repeated. After completion of the last logging, the scissors apparatus lifts the electrodes from the soil and stores them in the travel position. A small printed circuit board provides the necessary time delays for reading and logging operations. The mobile unit then moves to the next measurement site. All measurements at each site can be made in about 30–45 s. An earlier version of the above described equipment and some other examples of its utilization are discussed by Rhoades (1992a,b, 1994). A Cooperative Research and Development Act contract has been developed with AG Industrial Manufacturing of Lodi, CA to commercialize this system. For more on the engineering and design of this system, see Carter et al., 1993. Other simpler mobile, EM-systems have been developed to map soil salinity (Cannon et al., 1994).

With the combined EM/four-electrode equipment and limited calibration data, salinity distributions within the rootzone can be inferred. Example distributions are given in Fig. 6 for the furrow-irrigated and tile-drained field shown in Fig. 4. Relatively lower salinities occurred in this field in the soil overlying the tile-lines and higher salinities occurred in the soil located in between the tile lines. Additionally in this field,

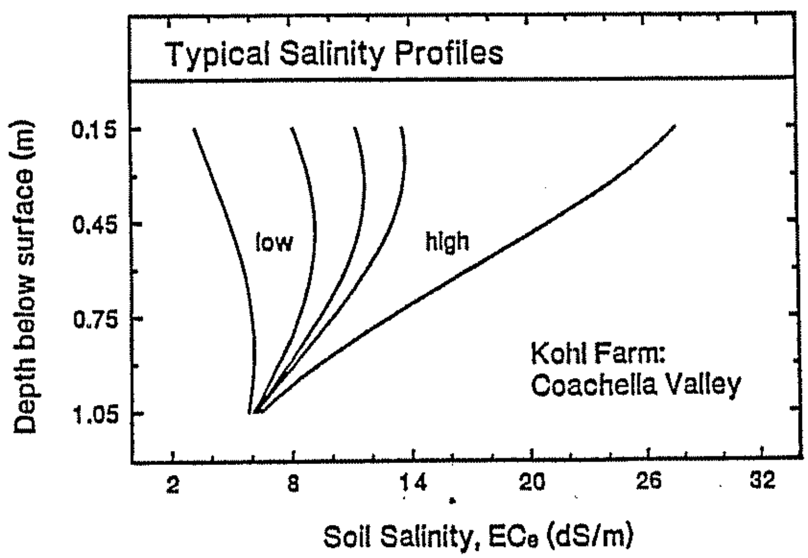

Fig. 6. Relation between salinity distribution and mean level of salinity in a tile-drained field (silty loam soil) located in the Coachella Valley of California.

as shown in Fig. 6, the distribution of salinity in the soil profile varied in relation to the mean level of salinity (which in turn varied in relation to the tile-line location). These distributions and relations imply, since the field was not deficit irrigated, that salinity is high in the areas of the field where the net flux of water has been upward in the field (in the region of the field located in between the drain lines) and is low in the areas (in the regions overlying the drain lines) where the net flux has been downward, that is where leaching has occurred. These data show that the salinity distribution(s) in the rootzone of an irrigated and tile-drained field can be used to infer the direction(s) of net water flux occurring in the different areas of the field and, hence, to assess the adequacy of the drainage system in interaction with the on-going irrigation management (the two are interrelated) existing there. In this case, the drainage system is concluded to be inadequate given the manner of irrigation, or geohydrologic situation, or both, existing in the field; since the level of salinity in the rootzone is excessive for normal crop production and the net flux of water is upward over too much of the field. A more quantitative discussion of how the distribution of salinity within the soil profile can be used to infer leaching/drainage adequacy is given later.

The salinity distributions in the upper part of the rootzone (0–0.5 m) of the same Coachella Valley field involved in Figs. 4 and 6 are portrayed in Fig. 7. These data indicate that the salinity levels and patterns within the seedbed of much of this field are

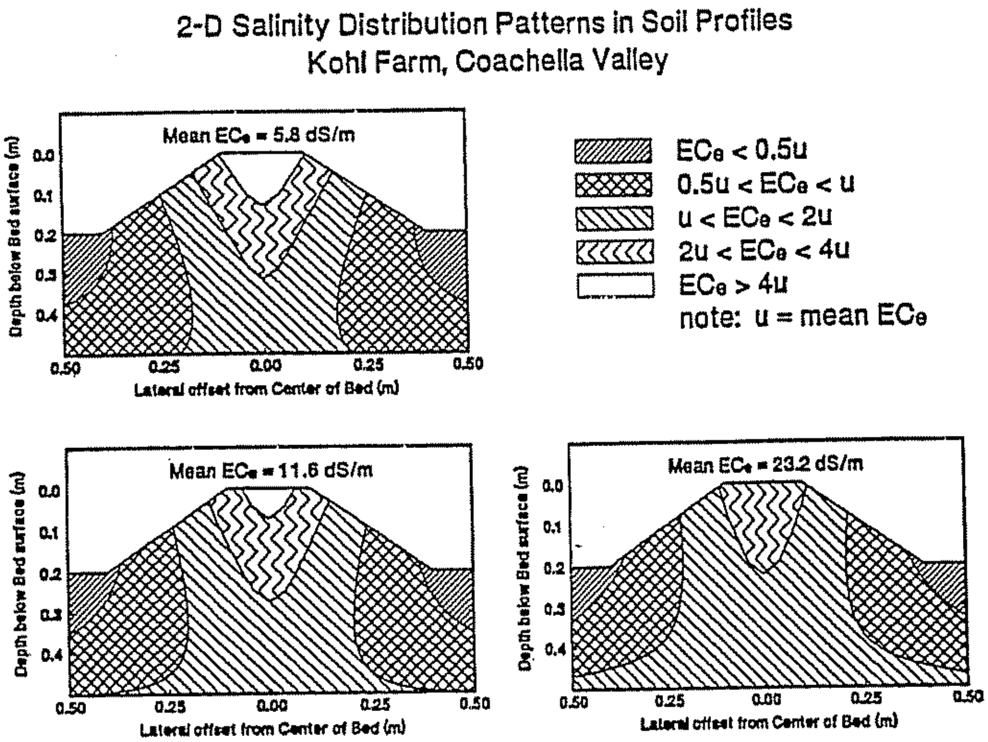

Fig. 7. Two-dimensional distributions of salinity in the upper half-meter of the soil profiles of a field located in the Coachella Valley of California, as influenced by mean (0–0.5 m) salinity level.

Table 1
Percent area of Borba-farm field with soil salinities (EC_e basis)within various ranges

Soil salinity (dS/m)	Soil depth (m)				
	0–0.3	0.3–0.6	0.6–0.9	0.9–1.2	0–1.2
0–2	14	44	17	15	3
2–4	41	32	34	31	49
4–8	36	17	22	25	29
8–16	9	6	16	17	16
> 16	0	1	10	11	2

Table 2
Percent area of furrow-irrigated, Borba-farm field by different soil salinity (EC_e basis)—depth profile types

Profile ratio	Profile type	% Area
> 0.75	very negative leaching	5
0.50–0.75	negative leaching	23
0.35–0.50	excess leaching	17
0.20–0.35	normal leaching	35
< 0.20	low leaching	20

not only excessively high but also are related to the mean profile salinity levels, which in turn are related to the drainage pattern. These data further indicate that the drainage system in this field is inadequate. The salinity distributions in this silty–loam soil are clearly two-dimensional, as would traditionally be expected under conditions of furrow irrigation. These results are in contrast to the one-dimensional profiles observed in clay textured, 'cracking' Imperial Valley soils. The data and reasons for this difference are given elsewhere (Rhoades et al., 1997).

Salinity 'distribution' data obtained with the 'combination sensor system' in two other fields (both near each other in the San Joaquin Valley of California) are given in Tables 1–3 to further illustrate how information about the levels and distributions of salinity within the rootzone obtained with this equipment can be used to evaluate the adequacies of salinity control and irrigation and drainage management. The percentages of the Borba-farm field having levels of salinities with certain ranges are given in Table 1. By reference to salt-tolerant tables, one can estimate how much yield loss caused by

Table 3
Percent area of sprinkler-irrigated, field by different soil salinity (EC_e basis)—depth profile types

Profile ratio	Profile type	% area
> 0.75	very negative leaching	0
0.50–0.75	negative leaching	3
0.35–0.50	excessive leaching	13
0.20–0.35	normal leaching	71
< 0.20	low leaching	13

such salinity conditions would result for any given crop. For example, assuming the crop is alfalfa (which has a threshold EC_e value of 2.0 dS/m and rate of yield loss of 13% for each unit of EC_e in excess of 2.0; Maas, 1990) and its effective depth of rooting is 1.2 m, one would estimate the relative yield loss due to salinity to be as follows by percentages of the Borba field: 0% loss in 3% of the field, 14.6% loss in 49% of the field, 44% loss in 29% of the field, and 100% loss in 18% of the field. Thus, on a whole field basis, the expected salinity induced loss in relative alfalfa yield would be 38%. The economic significance of this yield loss in turn can be calculated given other cost information and used to evaluate the economic impact of salinity on the profit-line of the operation of this field and also to evaluate the affordability of improving the management to eliminate the salinity-induced yield losses.

As explained earlier, the information of salinity by depth and location in the soil profiles of irrigated fields acquired by the 'combination system' can also be used to assess the adequacy of the past leaching and drainage practices. For example, where salinity is high in the near-surface soil of non-deficit irrigated fields and decreases with depth in the profile, the net flux of water (and salt) can be inferred as having been upward. This is reflective of inadequate drainage. Where salinity increases with depth in the profile, the net flux of water and salt can be inferred as having been downward. When salinity is low and relatively uniform with depth, leaching can be inferred as having been excessive, probably contributing to water-logging elsewhere. As shown previously (Table 29 in Rhoades et al., 1992), an approximate relationship can be established between steady-state leaching fraction (L) and the ratio: EC_e in the top-half of the rootzone/the sum of EC_e throughout the profile. This relationship (see Fig. 8) between L and the latter ratio (salinity profile ratio, P) is: $L = 0.01843\ (e^{8.0P})$. Thus,

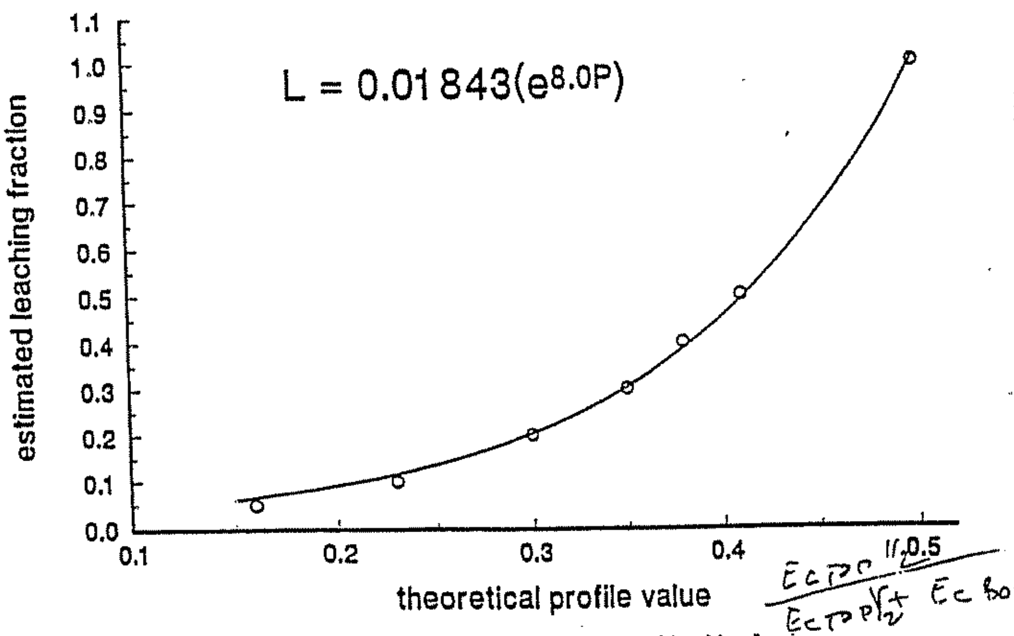

Fig. 8. Relationship between the salinity profile value and leaching fraction.

one can infer the approximate degree of leaching from the salinity profile ratio, which, in turn, can be determined from the data acquired with the 'combination system'. As an example, the percentages of a furrow-irrigated cotton field in the San Joaquin Valley of California are given in Table 2 by classes of profile values. Inverted salinity profiles (values > 0.50) occurred in 28% of this field. Such profiles are indicative of the net upward flux of water for the reasons previously given. We speculate, knowing that the irrigator applied water in excess of ET in this field, that excessive deep percolation occurred in the pre-season and early-season irrigations, causing a 'mounded, perched' water table which was the source of the water and salt that subsequently 'subbed' back up into the rootzone. Profiles with salinity distributions indicative of excessive leaching without causing mounding and the subsequent upflux (L values of greater than 0.3; salinity profile values of 0.35–0.50) occurred in 17% of the field, and profiles with salinity distributions indicative of normal leaching (L values of less than 0.3; salinity profile values < 0.35; salinity increasing with depth) occurred in only 55% of the field. Such data indicate that the leaching/drainage management is inadequate over much of the field. The analogous percentages obtained in a nearby San Joaquin Valley field (this one sprinkler irrigated) are given in Table 3. While both fields were of the same soil type (SiCL) and water table depth (~ 1.5 m), quite different results were obtained. Hardly any of the sprinkler-irrigated field had inverted (upward-flux) profiles; the desired normal leaching profiles were evident over 84% of the field. These examples show the improved irrigation, drainage and salinity management that can result from the use of the more efficient and uniform method of sprinkler irrigation compared to furrow-irrigation. These data further illustrate the utility of the assessment system and of detailed spatial information of soil salinity and its distribution through the rootzone to evaluate the adequacy and effectiveness of irrigation and drainage systems and practices. Maps of the areas with excessive leaching or of inadequate drainage can easily be prepared from these data to display the areal extent and locations of these areas. It may be possible to further quantify the degree of leaching in such areas from knowledge of salinity distributions and patterns, provided drainage is adequate, using salt balance approaches and additional spatial data of water applications and evapotranspiration, as suggested shown elsewhere (Rhoades, 1980, 1981; Slavich and Yang, 1990; Dowling et al., 1991), but more research is needed in this regard.

Besides irrigation and drainage, tillage and tractor traffic-patterns have been observed in some of our intensive, spatially referenced data sets to significantly affect soil salinity levels and distributions in fields. Tractors typically move through the fields in a systematic way, as dictated by the invoked practices of seedbed/furrow preparation, cultivation and tillage. As a result, tractor weight is repeatedly exerted in some furrows, but not in others, leading to cyclic patterns of compaction among some sequential sets of neighboring furrows. Similarly, tillage and cultivation operations are often implemented using equipment with guide/depth wheels which similarly lead to other analogous definable 'traffic' patterns. As a result, some furrows can become more compacted than others leading to reduced water-intake rates and to relatively increased lateral water flow rates and, hence, to higher salinity levels in both the associated furrows and beds. Systematic, cyclic differences observed in the salinity patterns of some irrigated fields surveyed with the 'combination' equipment were found to 'mimic' the traffic patterns undertaken with the tillage equipment. An example is shown in Fig. 9, in which the EC_a readings obtained in a succession of neighboring furrows are presented. The furrows in which the tractor tires travelled are indicated by an inverted triangle. The EC_a values associated with the spline fit (the plot of the 'running average' of neighboring values) of the readings are indicated by the dotted line. The differences between the individual EC_a values for each furrow and its spline-fitted value are presented in Fig. 9b. These data show that EC_a is substantially higher in each furrow the tractor tires travelled compared to its neighboring furrows. They also show that EC_a is substantially lower in each furrow that is 'sandwiched' between 'travelled' furrows. The other furrows have EC_a values that are only slightly higher, or lower, than its neighbors, as would be expected if

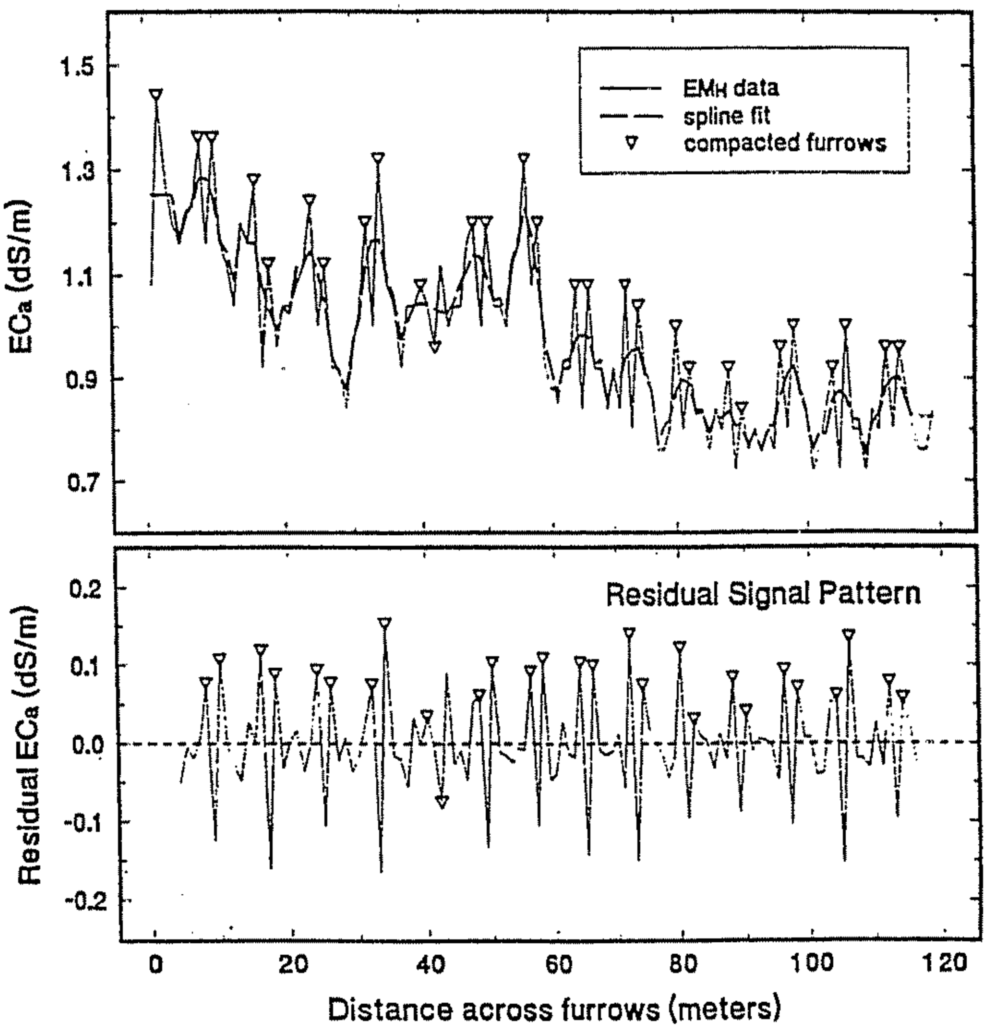

Fig. 9. Cyclic pattern of soil electrical conductivity across a succession of furrows, some trafficked by a tractor and some not.

there was no cyclic pattern or significant difference between them (that is, if all the furrows were essentially the same in their degree of compaction). The observed salinity pattern across this succession of furrows was clearly cyclic in nature and related to the tractor traffic pattern that had been followed in the field. In some fields displaying this phenomenon, the EC_e values in adjacent beds of furrow-irrigated fields have differed from their neighbors by as much as 4 dS/m, or more. Analogous cyclic patterns of soil salinity have been observed in other 'surveyed' fields that were caused by deep chiselling actions of subsurface tillage operations. In this case, the data obtained led to the inference that water had infiltrated and flowed preferentially in the tillage 'slits' and then flowed horizontally out into the adjacent soil causing salinity to be lower in the vicinity of the 'slit' compared to the inter-slit soil areas (data not shown). In one 'surveyed' field which had been 'ripped' to 0.5 m with chisels, markedly abrupt cyclic patterns of EC_a were observed that mimicked the tillage pattern. An excavation and detailed examination of the soil profile was made at the cyclic locations where the abrupt changes in EC_a were measured. This examination revealed (once the topsoil was removed) the presence of deep narrow trenches, or cracks, approximately 2.5 cm wide in the soil underlying the 'disced' topsoil. An interesting feature of these 'cracks' was that they were full of dry aggregates of *surface soil* that had fallen down into them. Hence, such 'cracks' not only provide preferential paths for water flow, but as well provide a means for soil particles and associated organic matter to 'fall' to deeper depths in the soil profile and thus a means by which certain pesticides and other relatively immobile chemicals may translocate in soils that is not accounted for in classical solute transport theory. This observation would not have been made without the use of our detailed spatial measurement system.

3. Salinity conversion and mapping theory / software

Several of the examples given above to show the utility of the assessment equipment involved results expressed in terms of soil salinity, as conventionally determined using soil samples and laboratory procedures. The most effective use of the mobile sensor-systems described above requires a rapid, accurate method for converting EC_a measurements to EC_e values. The various ways that EC_a may be measured and that EC_e may be determined from EC_a are reviewed by Rhoades (1993). EC_e can be predicted from EC_a with sufficient accuracy for the practical needs of salinity assessment using knowledge, or reasonably accurate estimates, of the clay and water contents existing in the soil profile at each EC_a measurement site (Rhoades et al., 1989b, 1990). While this method is suitable when EC_a measurements are made by hand-held equipment, it is impractical for the large numbers of sites sampled with the mobile assessment systems. For this reason, we developed a practical methodology to estimate soil salinity from extensive EC_a survey data, using limited calibration data of EC_e, various surface-trend parameters and multiple linear regression (MLR; Lesch et al., 1992). These 'MLR' techniques were shown to be theoretically equivalent to geostatistical, cokriging techniques, but to be more cost-effective and practical, (Lesch et al., 1995a,b). The MLR technique is an appropriate method when the secondary data can be acquired quickly and cheaply and where a strong correlation exists between the primary and secondary variables. This last requisite involving correlations between EC_e and EC_a was previously validated by Rhoades et al. (1989b, 1990). With the assessment system described herein, a series of easily obtained EM and/or four-electrode instrument readings are acquired across a field using a systematic survey scheme, the density of which varies with need and variability. A limited number of soil samples (typically about 8–12) are then acquired from a specially selected, subset of measurement-sites (as explained below) and measured for salinity (the rapid field method of Rhoades et al., 1989a is most practical for this purpose; Rhoades, 1996). A MLR equation, of the type shown in Eq. (1), is subsequently established with the co-located data and tested for residual spatial autocorrelation:

$$\log(EC_e) = \alpha_0 + \alpha_1[\log(EM_H)] + \alpha_2[\log(EM_H) - \log(EM_V)]. \quad (1)$$

If the residuals are independent (or reasonably so), the MLR approach is deemed adequate for salinity assessment involving the prediction, mapping, and monitoring of soil salinity. Kriging for interpolation purpose is used to predict salinity at sites where no secondary information (i.e., EC_a measurements) exists. The accuracy of the salinity predictions can be increased by incorporating the four-electrode data, as well as location coordinates, into the MLR equation. The uncertainty in the predictions of salinity are provided along with the predicted values. This methodology is explained in more detail elsewhere (Lesch et al., 1992, 1995a) and is contained within a software package that we developed to facilitate the implementation of the salinity assessment technology described herein and in the presentation and interpretation of the data (Lesch et al., 1995c).

An important requisite of the MLR approach is that the locations of the soil salinity calibration sites must be spatially representative of the entire survey area. This requisite was satisfied by implementing a newly developed spatial sampling procedure (Lesch et al., 1995b). The calibration site selection algorithm developed ensures that linear, quadratic and interaction terms in the MLR model can be accurately estimated. The algorithm also provides decision rules for selecting the final MLR model variables. Theory and tests of appropriateness of both the MLR approach and the calibration sampling/siting algorithm are described in detail elsewhere (Lesch et al., 1995a,b). The procedures are also given in the salinity assessment software package of Lesch et al. (1995c). Additionally, we have developed other software to process the mobile, four-electrode transect data for the purposes of plotting transect 'profiles', evaluating irrigation variability and producing salinity maps. The user manual for this software is presently in preparation.

A statistical test based on the above described MLR procedure/theory has also been developed and demonstrated to be suitable for monitoring changes in soil salinity over time, but will not be described in this paper for lack of space. A description of this methodology, as well as an example of its use for monitoring soil salinity, is given by Lesch et al. (1997).

4. Summary and conclusions

This paper describes an integrated package of instrumental systems and data-processing methodology for intensively measuring EC_a and x, y coordinates and for determining detailed spatial patterns of salinity within soil profiles and fields (for inventorying and monitoring soil salinity). It also presents examples of its utility for evaluating the appropriateness of the irrigation, drainage and tillage management practices (including determining the areal sources of irrigation-pollution) of which salinity is an indicator. The technology package described is unique and represents a breakthrough in our ability to rapidly and accurately assess soil salinity in irrigated lands.

Results presented in this paper show that much of the apparent chaos in the spatial pattern of soil salinity in irrigated fields is man-induced and related to the interacting irrigation, drainage, and tillage management practices. As our examples show, the particular edaphic and management practices causing the salinity patterns in individual fields can often be ascertained using the described integrated salinity assessment technology and procedures. Since salinity is a tracer of water flow, the instrumental systems and associated data analysis technology may have a much broader application than just salinity assessment. For example, the technology could potentially be used to identify or define the underlying rootzone and field-scale processes affecting the transport of individual solutes (i.e., nitrates or pesticides) in irrigated fields and to assess irrigation uniformity and degree of leaching.

References

Cannon, M.E., Mc Kenzie, R.C., Lachapelle, G., 1994. Soil salinity mapping with electromagnetic induction and satellite-based navigation methods. Can. J. Soil Sci. 74, 335–343.

Carter, L., Rhoades, J.D., Chesson, J.H., 1993. Mechanization of soil salinity assessment for mapping. Paper presented at 1993 Water Meeting of American Society of Agricultural Engineering, Chicago, IL, Dec. 12–17, 1993.

Dowling, A.J., Thorburn, P.J., Ross, P.J., Elliot, P.J., 1991. Estimation of infiltration and deep drainage in a furrow-irrigated sodic duplex soil. Aust. J. Soil Res. 29, 363–375.

Ghassemi, F., Jakeman, A.J., Nix, H.A., 1995. Salinization of land and water resources. University of New South Wales Press, Sydney, Aust., 526 pp.

Jury, W.A., 1975a. Solute travel-time estimates for tile-drained fields: I. Theory. Soil Sci. Soc. Am. J. 39, 1020–1024.

Jury, W.A., 1975b. Solute travel-time estimates for tile-drained fields: II. Application to experimental studies. Soil Sci. Soc. Am. J. 39, 1024–1028.

Kaddah, M.T., Rhoades, J.D., 1976. Salt and water balance in Imperial Valley, California. Soil Sci. Soc. Am. J. 40, 93–100.

Lesch, S.M., Rhoades, J.D., Lund, L.J., Corwin, D.L., 1992. Mapping soil salinity using calibrated electromagnetic measurements. Soil Sci. Soc. Am. J. 56 (2), 540–548.

Lesch, S.M., Strauss, D.J., Rhoades, J.D., 1995a. Spatial prediction of soil salinity using electromagnetic induction techniques: I. Statistical prediction models: A comparison of multiple linear regression and cokridging. Water Resour. Res. 31, 373–386.

Lesch, S.M., Strauss, D.J., Rhoades, J.D., 1995b. Spatial prediction of soil salinity using electromagnetic induction techniques: II. An efficient spatial sampling algorithm suitable for MLR model identification and estimation. Water Resour. Res. 31, 387–398.

Lesch, S.M., Rhoades, J.D., Strauss, D.J., Lin, K., Co, M.A.A., 1995c. The ESAP user manual and tutorial guide. Version 1.0, U.S. Salinity Laboratory Research Report #138, 108 pp.

Lesch, S.M., Herrero, J., Rhoades, J.D., 1997. Testing for changes in field salinity levels over time using electromagnetic induction techniques. Soil Sci. Soc. Am. J. (submitted).

Maas, E.V., 1990. Crop salt tolerance. In: Tanji, K.K. (Ed.). Agricultural Salinity Assessment and Management Manual. ASCE, New York, pp. 262–304.

Rhoades, J.D., 1980. Determining leaching fraction from field measurements of soil electrical conductivity. Agric. Water Manage. 3, 205–215.

Rhoades, 1981.

Rhoades, J.D., 1992a. Recent advances in the methodology for measuring and mapping soil salinity. Proc. Int. Symp. on Strategies for Utilizing Salt Affected Lands, Bangkok, Thailand, Feb. 17–25, 1992, pp. 39–58.

Rhoades, J.D., 1992b. Instrumental field methods of salinity appraisal. In: Topp, G.C., Reynolds, W.D., Green, R.E. (Eds.). Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice. SSSA Special Pub. No. 30, pp. 231–248.

Rhoades, J.D., 1993. Electrical conductivity methods for measuring and mapping soil salinity. In: Sparks, D.L. (Ed.). Advances in Agronomy, Vol. 49, 201–251.

Rhoades, J.D., 1994. Soil salinity assessment: Recent advances and findings. Proc. ISSS Sub-Commission Salt-Affected Soils Conference, Acapulco, Mexico, July 10–126, 1994. (In press).

Rhoades, J.D., 1996. Salinity: Electrical conductivity and total dissolved salts. In: Methods of Soil Analysis: Part 3. Chemical Methods, Soil Sci. Soc. Am. Book Series: 5, Am. Soc. Agronomy, Madison, WI, pp. 417–435.

Rhoades, J.D., Manteghi, N.A., Shouse, P.J., Alves, W.J., 1989a. Estimating soil salinity from saturated soil-paste electrical conductivity. Soil Sci. Soc. Am. J. 53 (2), 428–433.

Rhoades, J.D., Manteghi, N.A., Shouse, P.J., Alves, W.J., 1989b. Soil electrical conductivity and soil salinity: New formulations and calibrations. Soil Sci. Soc. Am. J. 53 (2), 433–439.

Rhoades, J.D., Shouse, P.J., Alves, W.J., Manteghi, N.A., Lesch, S.M., 1990. Determining soil salinity from soil electrical conductivity using different models and estimates. Soil Sci. Soc. Am. J. 54 (1), 46–54.

Rhoades, J.D., Kandiah, A., Mashali, A.M., 1992. The use of saline waters for crop production. FAO Irrigation and Drainage Paper 48, Food and Agriculture Organization of the United Nations, Rome, Italy, 133 pp.

Rhoades, J.D., Lesch, S.M., Burch, S.L., Letey, J.R., LeMert, D., Shouse, P.J., Oster, J.D., O'Halloran, T., 1997. Salt transport in soils of various shrink-swell properties Salt distributions in soil profiles and fields and salt pick-up by run-off waters. ASCE, J. Irrig. Drainage Eng.

Slavich, P.G., Yang, J., 1990. Estimation of field scale leaching rates from chloride mass balance and electromagnetic induction measurements. Irrig. Sci. 11, 7–14.

U.S. Salinity Laboratory Staff, 1954. Diagnosis and improvement of saline and alkalai soils. USDA Agric. Handbook 60, U.S. Govt. Printing Office, Washington DC, 160 pp.

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PHYSICAL AND CHEMICAL PROPERTIES OF MAJOR IMPERIAL VALLEY SOILS

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CONTENTS

PHYSICAL AND CHEMICAL PROPERTIES OF MAJOR IMPERIAL VALLEY SOILS 1/

Eugene R. Perrier, Arnold J. MacKenzie, and Robert P. Zimmerman 2/

INTRODUCTION

Knowledge of the soil's chemical and physical properties is required to interpret the crop production potential and to evaluate engineering and conservation practices. Although soil survey reports of observable physical characteristics of soil provide valuable information, interrelated physical and chemical measurements at standardized locations provide useful scales of reference in the establishment of soil management practices, such as tillage, irrigation, drainage, salt balance, and fertilization.

The alluvial soils of the Imperial Valley of California are composed of highly stratified Colorado River deposits, largely from mixed sedimentary rock material transported from the Grand Canyon area of Arizona. The variations in the soils are due mostly to textural differences caused by the manner and sequence in which the alluvial material was deposited. The deposits vary considerably in texture; both vertically and horizontally. Cropping and soil management practices for the approximately 500,000 acres of irrigated land within the Valley, in general, are affected and influenced predominantly by these soil textural characteristics. Since most of the variation within soil types appears to be due to texture, and since management practices vary due to textural differences, an evaluation was made of the relationships between soil texture as measured by particle size distribution and factors such as soil moisture retention, infiltration rate, hydraulic conductivity, surface area, and other physical and chemical characteristics.

1/ Contribution of the Agricultural Research Service (ARS) and the Soil Conservation Service (SCS), U.S. Department of Agriculture, in cooperation with the Illinois Agricultural Experiment Station.

2/ Soil scientist, ARS, and assistant professor of soil physics, Department of Agronomy, University of Illinois, Urbana, Ill.; soil scientist, ARS, Brawley, Calif.; and soil scientist, El Centro Work Unit, SCS, El Centro, Calif., respectively.

EXPERIMENTAL METHODS

Approximately 80 percent of the cultivated area in Imperial Valley can be classified within six phases representing four soil series as follows:

1. Imperial series (clays and silty or sandy clays more than 40 inches deep).
   a. Imperial silty clay.
2. Holtville series (fine textures -- clay to clay loam, overlying contrasting coarser textures at depths of 20 to 36 inches).
   a. Holtville silty clay (silty clay over loams to sandy loams).
   b. Holtville silty clay, sandy substratum (silty clay over loamy fine sands to fine sands).
3. Indio series (silt loams, loams, and very fine sandy loams more than 40 inches deep).
   a. Indio loam.
   b. Indio very fine sandy loam, sandy substratum (very fine sandy loam over loamy fine sands to fine sands).
4. Meloland series (medium or coarse textures -- loams to fine sands, overlying contrasting fine textures -- clays to clay loams, at depth of 16 to 35 inches).
   a. Meloland very fine sandy loam.

Sites for the six soil profiles were selected (fig. 1), and at each site a pit was dug. The soil profile description was recorded, and soil samples were taken for chemical and physical analysis. Bulk soil samples (300 pounds or 30 gallons) were taken from each significant layer as determined from the soil profile description.

PHYSICAL METHODS

The field soil samples were crushed and passed through a 2-mm sieve. Subsamples were taken from each layer and sent to the U.S. Salinity Laboratory, Riverside, Calif., where the fraction percentages of specific clay types were identified (7).[3] Particle-size distribution by pipette analysis (6) was measured by the Soil Survey Laboratory, SCS, Riverside, Calif. Additional subsamples from each site were sent to the California Division of Highways Laboratory, San Diego, Calif., where measurements of Atterburg constants (2) and maximum compaction density at optimum moisture were made.

3/ Underscored numbers in parentheses refer to Literature Cited, p. 18.

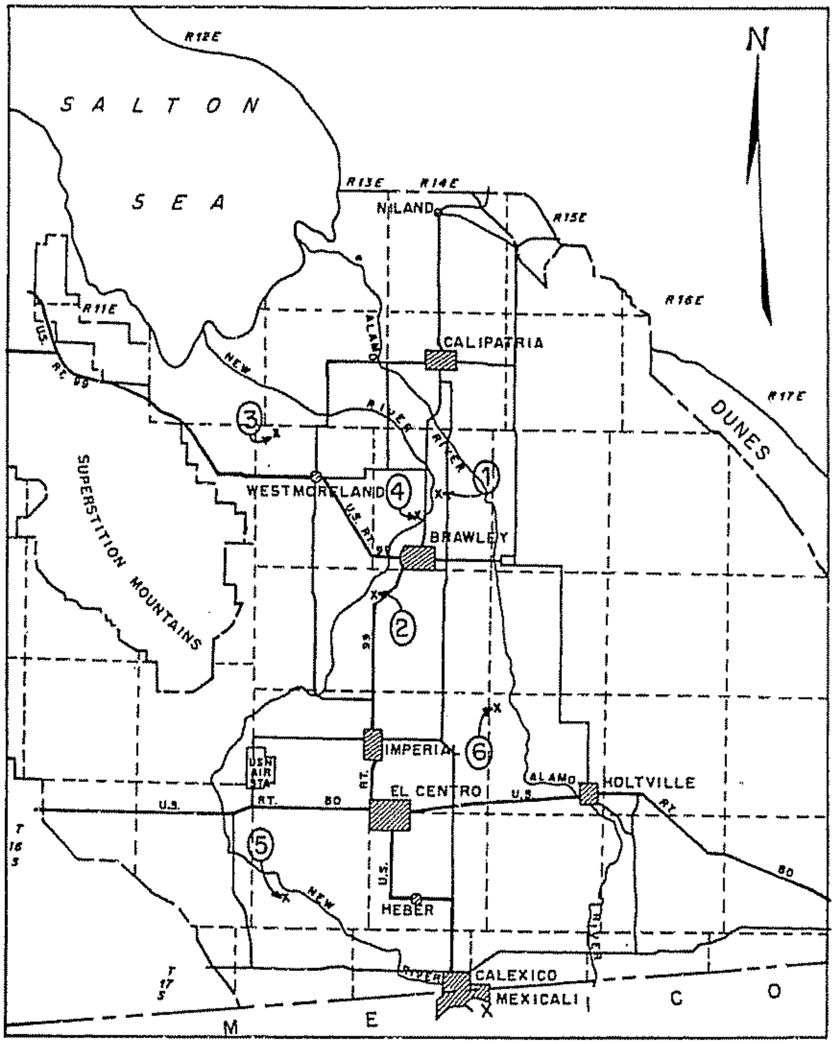

Figure 1 -- Location of sampling sites in Imperial Valley, Calif.

A Kelly core sampler (5) was used to obtain samples (four replications) for determining bulk densities for each soil layer at a specified depth. The average infiltration rate was determined at each site by use of six infiltrometer tubes (4), 12 inches in diameter by 24 inches in height.

Soil moisture retention curves on crushed sieved samples were obtained by means of pressure-plate apparatus (10) for suctions of 1 bar or less, and pressure-membrane apparatus (9) was used for suctions greater than 1 bar.

CHEMICAL METHODS

Soil salinity, soluble anions and cations, soil reaction (pH), cation exchange capacity and exchangeable cations, sodium adsorption ratios, and other determinations were made in accordance to procedures described in USDA Agricultural Handbook 60. Organic matter was determined by the method described by Aguilera and Jackson (1). Organic nitrogen was determined by the Kjeldahl method (3). Total phosphorus and the various phosphorus fractions were determined by methods outlined in "Methods of Soil Analysis" (8).

RESULTS

Soil Series

The soils in this study were all classified as Alluvial Soils in the 1938 USDA Yearbook, "Soils and Men". Before the new system of soil classification (about 1959), the soils studied here best fitted the Regosol concept of Azonal Soils. They are classified as Torriorthents and Torrifluvents (11).

Parent materials of the soils studied here are unweathered lacustrine sediments, largely from mixed sedimentary rock material transported by the Colorado River. The silts and fine sands of these sediments may have been reworked by wind. In the desert climate of the study area, these soils are well drained, but drainage phases under irrigated agriculture are the usual situation. The general slope of these soils on the old lake bed is nearly flat except along certain fault lines where vertical displacement has occurred. Locally, there is a dune microrelief in areas where sands and silts have been moved by wind.

These soils differ from each other and from associated soil series only in texture and stratification. Significant differences in texture of the control section (10 to 40 inches in depth) or significant strata of contrasting texture within the section are criteria for separation at family or series level.

The soils studied are used principally for irrigated agriculture and dominate mapping units that cover approximately 80 percent of the nearly 500,000-acre irrigated area of Imperial Valley. Of this 80 percent, Imperial silty clay comprises about 40 percent, Holtville mapping units about 20 percent, Meloland mapping units about 12 percent, and Indio mapping units about 8 percent.

Physiography

The soils of the study area all lie within the beach line of ancient Lake Cahuilla. Within this area on the lake plain, there are no consistent relationships between soils and surface features.

Climate

The climate of the Imperial Valley is hot and dry east of the Peninsula Coast Range of mountains in the low basin of the Colorado Desert and shut off from the moderating effects of the ocean. The rainfall is very low, because the region depends on the westerly winds from the Pacific Ocean for its supply of rain. These winds, in crossing the coastal mountain range, precipitate their moisture on the western slopes. They pass over the low desert basin (in general below sea level) as hot, arid winds.

The Imperial Valley (at El Centro) has an average annual rainfall of only 2.72 inches. Throughout the year, the relative humidity is fairly high for a desert region; the annual average being 30 percent. During July and August, the average relative humidity increases and does not decrease until sometime in September. In July and August, the prevailing winds change from westerly to southeasterly, which brings in moist air from the Gulf of California.

April and May are associated with the greatest wind velocities, and average 3.8 miles per hour daily. These climatic variations do not affect the normal distribution curve of evapotranspiration, because June, July, August, and September are essentially the same; the average being about one-third inch per day during this period. The climate is highly favorable for crops, an average of 314 days between frosts and 12 days of frost.

Description of Soil Series

Imperial Series

The soils of the Imperial series have a fine-textured control section, which usually contains less than 0.2-percent carbon, and is dry unless irrigated. These characteristics plus climatic setting and high shrink-swell ratio make it a Vertic Torriorthent. Imperial soils are in the fine, montmorillonitic (calcareous), hyperthermic family of the subgroup.

Holtville Series

The soils of the Holtville series have no diagnostic horizon. The control section contains strongly contrasting fine textures over loamy particle-size classes and is dry unless irrigated. The Holtville series is a member of a clayey over loamy, montmorillonitic (calcareous), hyperthermic family of Typic Torrifluvents. A taxadjunct of the Holtville series with a control section of fine over sandy particle-size classes is included in this study.

Meloland Series

The soils of the Meloland series have no diagnostic horizon. The control section contains strongly contrasting coarse loamy over fine particle-size classes and is dry unless irrigated. The Meloland series is a member of a coarse-loamy over clayey, mixed (calcareous), hyperthermic family of Typic Torrifluvents.

Indio Series

The soils of the Indio series have no diagnostic horizon. The coarse silty control section usually contains less than 0.2-percent carbon and is dry unless irrigated. The Indio series is a member of a coarse-silty, mixed (calcareous), hyperthermic family of Typic Torriorthents. A taxadjunct of the Indio series with a coarse silty over sandy control section is included in this study.

Soil Profile Descriptions

Profile 1:	Imperial Silty Clay
LOCATION:	Imperial County, Calif. Near center of NW1/4 N1/2 Tract 118, sec. 15, T 13 S., R. 14 E., San Bernardino Base Meridian. Approximately 1,170 feet west, 1,000 feet south of gate 116-AA, Best Lateral 1. From East Main Street, Brawley, 3 1/2 miles north along Best Canal, west 0.2 miles on Best Lateral 1 to Gate 116-AA.
CLASSIFICATION:	Vertic Torriorthent, fine montmorillonitic (calcareous) hyperthermic family.
VEGETATION:	Cultivated, fallow after sugar beets.
CLIMATE:	Annual average precipitation, 2.72 inches; average annual temperature, 72° F. Average frost-free growing season 314 days, January 29 to December 9.
PARENT MATERIAL:	Recent lacustrine sediments.
TOPOGRAPHY:	Lacustrine basin, nearly level, less than 1-percent slope to north.
ELEVATION:	150 feet below sea level.
DRAINAGE:	Runoff slow, permeability slow, well drained, water table not observed.
SOIL MOISTURE:	Dry in Ap, slightly moist below.
REMARKS:	pH determined by Truog color test. Very little variation of pH or effervescence. No coarse fragments. Platy structure noted, may be microstratification. Thick plates break with conchoidal fracture when dry. Minor strata of lighter texture are sometimes found at varying depths within the profile. Vertical cracks up to 1 inch wide and 6 feet deep, spaced about 1 foot apart, are sometimes filled with lighter textured materials.

Horizon	Depth Inches	Description
Ap	0-13	Pinkish-gray (7.5YR 6/2) silty clay, brown (7.5YR 5/4) moist; moderate coarse and very coarse subangular blocky; very hard, very firm, sticky and plastic; few very fine to coarse random exped roots; common very fine to fine discontinuous random pores; moderately alkaline (pH 8.1); strongly effervescent; few fine white gypsum efflorescences; clear smooth boundary.
C1	13-60	Light-brown (7.5YR 6/4) silty clay, brown (10YR 4/3) moist; weak medium to very coarse platy; very hard, very firm, sticky and plastic; very few very fine exped roots; moderately alkaline (pH 8.1); strongly effervescent; discontinuous horizontal lenses of loamy fine sand up to 2 inches thick at 42-inch depth. Common fine white gypsum efflorescences to a depth of 36 inches. Horizon arbitrarily sampled for characterization at 13- to 28-inch and 28- to 42-inch depths.

Profile 2: Holtville Silty Clay, Over Medium Textures

LOCATION: Imperial County, Calif. Tract 109, sec. 7, T. 14 S., R. 14 E., San Bernardino Base Meridian, in the ARS Imperial Valley Conservation Research Center Farm at the middle of north end of plot F-2, approximately 35 feet south of field road.

CLASSIFICATION: Typic Torrifluvent, clayey over loamy, montmorillonitic (calcareous), hyperthermic family.

VEGETATION: Cultivated, fallow after barley.

CLIMATE: Average annual precipitation 2.72 inches; average annual temperature, 72° F. Average frost-free growing season 314 days, January 29 to December 9.

PARENT MATERIAL: Recent lacustrine sediments.

TOPOGRAPHY: Lacustrine basin, nearly level, less than 1-percent slope to north.

ELEVATION: 90 feet below sea level.

DRAINAGE: Runoff slow, permeability slow, well drained, water table not observed.

SOIL MOISTURE: Dry in Ap, slightly moist below.

REMARKS: pH determined by Troug color test. Very little variation of pH or effervescence. No coarse fragments. Platy structure noted may be microstratification.

Horizon	Depth Inches	Description
Ap	0-10	Pinkish-gray (7.5YR 6/2) silty clay, brown (7.5YR 4/2) moist; weak coarse subangular blocky and weak very coarse platy; very hard, very firm, sticky, and plastic; few fine and very fine random roots; mildly alkaline (pH 7.8); strongly effervescent; clear smooth boundary.
C1	10-22	Light-brown (7.5YR 6/4) silty clay, brown (7.5YR 4/2) moist; weak medium subangular blocky and weak very coarse platy; very hard, firm, sticky and plastic; few fine and very fine random roots; few discontinuous very fine pores; mildly alkaline (pH 7.8); strongly effervescent; vertical lenses of silt, few fine white gypsum efflorescences; abrupt smooth boundary.
C2	22-33	Light-brown (7.5 YR 6/4) silty clay, brown (7.5YR 4/4) moist; moderate coarse platy; very hard, friable, slightly sticky and plastic; few fine and very fine roots; mildly alkaline; strongly effervescent; horizontal silty partings; few fine and medium gypsum efflorescences in cracks; clear smooth boundary.
C3	33-50	Pink (7.5YR 7/4) loam matrix, yellowish brown moist, with light-brown (7.5YR 6/4) silty clay microstrata, brown (7.5YR 5/4) moist; massive; hard, friable, nonsticky and slightly plastic; very few very fine roots in vertical cracks; mildly alkaline; strongly effervescent; loam strata 1/2 to 1 inch thick interbedded with silty clay partings up to 1/4 inch thick; few fine distinct rusty stains; slight cross bedding; vertical cracks up to 1/2 inch thick filled with silty clay loam; clear smooth boundary.

C4	50-56	Pink (7.5YR 7/4) loamy very fine sand, light yellowish brown (10YR 6/4) moist; massive; slightly hard, very friable, nonsticky and slightly plastic; few very fine roots in vertical cracks; mildly alkaline (pH 7.8); strongly effervescent; microstrata crossbedded; clear wavy boundary.
C5	56-66	Very pale-brown (10YR 7/3) very fine sandy loam matrix, light yellowish brown (10YR 6/4) moist; with pale-brown (10YR 6/3), very fine sandy loam horizontal microstrata, brown (10YR 4/3) moist; massive; slightly hard, friable, nonsticky and slightly plastic; very few very fine roots in vertical cracks; mildly alkaline (pH 7.8); strongly effervescent; slightly crossbedded microstrata with matrix layers 1/8 inch thick separated by 1/16 inch thick minor strata.

Profile 3: Holtville Silty Clay Taxadjunct, Coarse-Textured Substrata

LOCATION: Imperial County, Calif. Near center E1/2 SW1/4 Tract 130, sec. 6, T. 13 S., R. 13 S., R. 13 E., San Bernardino Base Meridian, approximately 250 feet west, 700 feet north of gate 179, Trifolium Lateral 9, 2 1/4 miles north of U.S. Highway 99 along Trifolium Lateral 9.

CLASSIFICATION: Typic Torrifluvent, clayey over sandy, montmorillonitic (calcareous), hyperthermic family.

VEGETATION: Fallow after cotton.

CLIMATE: Average annual precipitation, 2.72 inches; mean annual temperature, 72° F. Average frost-free growing season 314 days, January 29 to December 9.

PARENT MATERIAL: Recent lacustrine sediments.

TOPOGRAPHY: Lacustrine basin, nearly level, less than 1-percent slope to the north.

ELEVATION: 190 feet below sea level.

DRAINAGE: Slow runoff, permeability is slow over moderately rapid. Well drained.

SOIL MOISTURE: Moist.

REMARKS:	Truog color test used to determine pH. Vertical cracks approximately 2 inches wide filled with loamy fine sand in the fine-textured horizons. Few minor strata of fine-textured material in coarse-textured substrata.

Horizon	Depth Inches	Description
Ap	0-17	Light-brown (7.5YR 6/4) silty clay, yellowish brown (10YR 5/4) moist; massive and weak, medium subangular blocky; very hard, very firm, sticky and very plastic; common very fine and few fine random roots; few very fine random tubular pores; moderately alkaline (pH 8.0); strongly effervescent; clear smooth boundary.
C1	17-24	Light-brown (7.5YR 6/4) silty clay, brown (7.5YR 5/4) moist; moderate, medium platy; very hard, firm, very sticky and very plastic; few fine random roots; common very fine random tubular pores; moderately alkaline (pH 8.0); strongly effervescent; clear smooth boundary.
C2	24-35	Very pale-brown (10YR 7/3) loam, brown (10YR 5/3) moist; massive; slightly hard, friable, slightly sticky and slightly plastic; common very fine random roots; many very fine random tubular pores; moderately alkaline (pH 8.0); strongly effervescent; abrupt smooth lower boundary.
C3	35-72	Very pale-brown (10YR 7/3) loamy fine sand, brown (10YR 5/3) moist; single grain; weakly coherent, very friable, nonsticky and non-plastic; very few fine random tubular pores; moderately alkaline (pH 8.0); strongly effervescent.

Profile 4:	Meloland Loam
LOCATION:	Imperial County, Calif. Near center of north side of NE1/4 NE1/4 Tract 93, sec. 16, T. 13 S., R. 14 E., San Bernardino Base Meridian. Approximately 175 feet south, 1,150 feet east of bridge over Spruce 3 drain on Highway 111.
CLASSIFICATION:	Typic Torrifluvent, coarse loamy over clayey, mixed (calcareous), hyperthermic family.

VEGETATION: Fallow after cotton.

CLIMATE: Average annual precipitation, 2.72 inches; average annual temperature, 72° F. Average frost-free growing season 314 days, January 29 to December 9.

PARENT MATERIAL: Recent lacustrine sediments.

TOPOGRAPHY: Lacustrine basin, nearly level, less than 1-percent slope to north.

ELEVATION: 150 feet below sea level.

DRAINAGE: Well drained.

SOIL MOISTURE: Slightly moist.

REMARKS: pH determined by Truog color test. Very little variation pH or effervescence. No coarse fragments. Platy structure noted may be microstratification. Thin strata of lighter texture found within the fine textured substrata in some places.

Horizon	Depth Inches	Description
Ap	0-12	Light-brown (7.5YR 6/4) loam, brown (7.5YR 5/4) moist; massive; slightly hard, very friable, slightly sticky and plastic; few medium and coarse roots, many fine and very fine random roots; mildly alkaline (pH 7.8); violently effervescent; abrupt smooth boundary.
C1	12-18	Very pale-brown (10YR 7/3) loamy fine sand, brown (10YR 5/3) moist; massive and single grain; weakly coherent, very friable, nonsticky and slightly plastic; few fine to very fine horizontal roots; mildly alkaline (pH 7.8); violently effervescent; microstrata crossbedded; abrupt wavy boundary.
C2	18-26	Very pale-brown (10YR 7/3) silt loam, brown (10YR 5/3) moist; massive; hard, friable, slightly sticky and plastic; few fine and very fine random roots; common fine and very fine tubular pores with rusty linings; mildly alkaline (pH 7.8); violently effervescent; intermittent horizontal lenses of very fine sandy loam up to 2 inches thick at 19 inches, intermittent horizontal lenses of silty clay up to 2 inches thick at 23 inches; abrupt wavy boundary.

C3	26-38	Pink (7.5YR 7/4) clay, brown (7.5YR 5/4) moist; moderate very fine platy structure; very hard, firm, very sticky and very plastic; few very fine vertical and horizontal roots; few very fine tubular vertical pores; mildly alkaline (ph 7.8); strongly effervescent; few fine white gypsum efflorescences; thin vertical cracks spaced about 1 foot apart filled with loamy very fine sand; gradual smooth boundary.
C4	38-53	Pink (7.5YR 7/4) clay, brown (7.5YR 4/4) moist; massive; very hard, very firm, very sticky and very plastic; few fine roots in vertical cracks and irregular fractures; mildly alkaline (pH 7.8); strongly effervescent; many large white gypsum efflorescences in vertical cracks and irregular fractures; diffuse smooth boundary.
C5	53-71	Pink (7.5YR 7/4) clay, brown (7.5YR 4/4) moist; massive; very hard, firm, very sticky and very plastic; few very fine random roots; very few, very fine discontinuous tubular pores; mildly alkaline (pH 7.8); strongly effervescent with disseminated carbonates; many large white gypsum efflorescences in vertical cracks and irregular fractures to 59 inches, common medium rusty stains below 59 inches.

Profile 5: Indio Loam

LOCATION: Imperial County, Calif. Near the center of the NE 1/4 NE 1/4, sec. 29, T. 16 S., R. 13 E., San Bernardino Base Meridian, approximately 850 feet east, 400 feet north of gate 123, Wisteria Lateral 8. About 0.4 miles west of Wulf's Crossing and south of New River.

CLASSIFICATION: Typic Torriorthent, coarse-silty, mixed (calcareous) hyperthermic family.

VEGETATION: Cultivated, disked up after lettuce harvest.

CLIMATE: Average annual precipitation, 2.72 inches; average annual temperature, 72° F. Average frost-free growing season, 314 days, January 29 to December 9.

PARENT MATERIAL: Recent lacustrine sediments.

TOPOGRAPHY: Lacustrine basin, nearly level, less than 1-percent slope toward north.

ELEVATION: 25 feet below sea level.

DRAINAGE:	Runoff slow, permeability moderately slow, well drained, water table not observed.
SOIL MOISTURE:	Dry in Ap, slightly moist below.
REMARKS:	pH determined by Truog color test. Very little variability of pH, or effervescence; no coarse fragments. Platy structure noted may be microstratification. Contrasting minor strata of coarser or finer textures may be at any depth. Vertical cracks 1/8 to 1/4 inch thick, 3 to 12 inches apart, up to 5 feet deep, filled with material from upper horizons. Crossbedding may be result of reworking by wind.

Horizon	Depth Inches	Description
Ap	0-12	Pinkish-gray (7.5YR 6/2) loam, dark gray-brown (10YR 4/2) moist; moderate medium subangular blocky; slightly sticky and slightly plastic; plentiful very fine random roots; few very fine pores; moderately alkaline (pH 8.2); strongly effervescent; abrupt wavy boundary.
C1	12-30	Very pale-brown (10YR 7/3) very fine sandy loam, brown (10YR 4/3) moist; massive and weak fine platy; slightly hard, very friable, nonsticky and nonplastic; few very fine random roots; very few very fine pores; moderately alkaline (pH 8.2); strongly effervescent; crossbedding in microstrata approximately 1 mm thick; few fine distinct rusty stains in cracks; gradual wavy boundary.
C2	30-44	Pink (7.5YR 7/4) loamy very fine sand, brown (10YR 5/3) moist; massive and weak fine platy structure; weakly coherent, very friable, nonsticky and nonplastic; few very fine random roots; very few very fine pores; moderately alkaline; strongly effervescent; crossbedded microstrata approximately 5 mm thick, few large strong brown (7.5YR 5/6) moist stains in cracks, diffuse wavy boundary.
C3	44-58	Pink (7.5YR 7/4) loamy very fine sand, brown (10YR 5/3) moist; massive and weak fine platy; soft, very friable, nonsticky and nonplastic; very few very fine vertical and horizontal roots; common very fine and fine continuous dendritic open pores with dark linings; moderately alkaline (pH 8.2); strongly effervescent; crossbedded microstrata about 5 mm thick; diffuse wavy boundary.

C4	58-72	Pink (7.5YR 7/4) loamy very fine sand, pale brown (10YR 6/3) moist; massive and weak fine platy structure; soft, very friable, nonsticky and nonplastic; very few very fine vertical and horizontal roots; few very fine to fine continuous dendritic pores; moderately alkaline; strongly effervescent; crossbedded microstrata about 5 mm thick.

Profile 6: Indio Very Fine Sandy Loam Taxadjunct, Deep Over Coarse Textures

LOCATION: Imperial County, Calif. Near the center of E1/2 lot 14, sec. 6, T. 15 S., R. 15 E., San Bernardino Base Meridian, approximately 530 feet west, 550 feet north of the headgate of Redwood Lateral 1. 4 1/2 miles north, 3/4 mile west of Meloland Experiment Station.

CLASSIFICATION: Typic Torriorthent, coarse-silty over sandy, mixed (calcareous) hyperthermic family.

VEGETATION: Barley stubble.

CLIMATE: Average annual precipitation, 2.72 inches; average annual temperature, 72° F. Average frost-free growing season, 314 days, January 29 to December 9.

PARENT MATERIAL: Recent lacustrine sediments.

TOPOGRAPHY: Lacustrine basin, nearly level, less than 1-percent slope toward north.

ELEVATION: 100 feet below sea level.

DRAINAGE: Runoff medium, permeability moderately slow, well drained, water table at 73 inches.

SOIL MOISTURE: Dry in Ap, noted below.

REMARKS: pH determined by Truog color test. Very little variability of pH or effervescence. Platy structure notes, may be microstratification. No coarse fragments. Crossbedding may be result of reworking by wind.

Horizon	Depth Inches	Description
Ap	0-13	Pink (7.5YR 7/4) very fine sandy loam, brown (7.5YR 5/4) moist; moderate medium subangular blocky structure; slightly hard, friable, nonsticky and slightly plastic; common very fine and fine random roots and few medium vertical roots; common very fine and fine continuous random exped pores; moderately alkaline (pH 8.2); violently effervescent with disseminated carbonates; clear wavy boundary.
C1	13-27	Pink (7.5YR 7/4) very fine sandy loam, brown (7.5YR 5/4) moist; massive and weak coarse platy structure; slightly hard, very friable, nonsticky and slightly plastic; common very fine random roots; few fine horizontal roots; common very fine continuous random pores; moderately alkaline (pH 8.2); violently effervescent; few fine rusty stains in thin vertical and horizontal cracks; faint crossbedding; gradual wavy boundary.
C2	27-37	Pink (7.5YR 7/4) loam; brown (7.5YR 5/4) moist; massive; slightly hard, friable, slightly sticky and slightly plastic; few very fine random roots; few very fine random pores; moderately alkaline (pH 8.2); violently effervescent; rusty stains in pores and fractures; abrupt smooth boundary.
C3	37-72	Very pale-brown (10YR 7/4) loamy fine sand, light brown (7.5YR 6/4); single grain; loose, nonsticky and nonplastic; moderately alkaline (pH 8.2); strongly effervescent; crossbedded to 42 inches, horizontal bedding below 42 inches, accumulation of soft black nodules 58 to 62 inches.

Physical Measurements

The clay fraction analyzed are presented in table 1 [4/] and confirm that clayey soils should be classified montmorillonitic as this clay type was predominant in all samples analysed. The particle-size distribution analysis is shown in table 2 for a wide range of sieve fractions. The Atterburg constants and the maximum compaction density at the optimum moisture content are presented in table 3. Table 4 shows the moisture retention data, and table 5 presents the average soil bulk density determinations. The average soil surface infiltration rates for the six soils are given in table 6.

4/ All tables are grouped together at the end of this report.

Chemical Measurements

The chemical analyses of soil salinity, soluble anions and cations, pH, exchange capacity, gypsum, calcium carbonate, free iron oxides, exchangeable sodium and potassium, sodium adsorption ratio, and other determinations are given in tables 7 and 8. The organic nitrogen, organic carbon, and organic matter analyses are shown in table 9. Table 10 presents the chemical analyses of total phosphorus and the various phosphorus fractions.

Relations Between Clay Content (<2μ) and Physical and Chemical Properties

To assist in comparing and interpreting the interrelationships of the physical and chemical properties of Imperial Valley soils, the data were entered into an IBM 360-75 computer, and various correlations and linear regression analyses were made. The results comparing clay content (<2μ) to various physical and chemical properties are given in table 11. Significant correlation coefficients were obtained for the relations between clay content and moisture retention (at all suctions), liquid limit, plastic index, saturation percentage, cation exchange capacity, gypsum content, free iron oxides, total surface area, organic matter, organic nitrogen, and total phosphorus.

Relations Between Saturation Percentage and Physical and Chemical Properties

Clay content (<2μ) was well correlated with many physical and chemical properties including the saturation percentage. Because of the ease in determining saturation percentage, an analysis of these relations to soil properties was made (table 12). The saturation percentage data gave the same levels of significance as obtained by the clay content. By using the linear relationships found between the easily determined saturation percentage and other more difficult to measure soil properties, the other more difficult to measure soil properties can be predicted or estimated.

Relations Between Sodium Adsorption Ratio and Some Selected Chemical Properties

The results of correlation analyses comparing sodium adsorption ratio (SAR) to exchangeable sodium percentage (ESP) and pH are given in table 13. No significant relation was found between SAR and ESP, but a significant correlation coefficient was obtained for the relation between SAR and pH. The relation between ESP and pH was not significant.

LITERATURE CITED

(1) Aguilera, N. H., and Jackson, M. L.
1952. Iron oxide removal from soils and clays. Soil Sci. Soc. Amer. Proc. 17:359-364.

(2) Baver, L. D., Gardner, W. H., and Gardner, W. R.
1972. Soil physics. 498 pp. New York.

(3) Bremner, J. M.
1965. Total nitrogen. In Black, C. A. ed., Methods of Soil Analysis, part 2:1149-1178. American Society of Agronomy, Inc., Madison, Wis.

(4) Haise, H. R., Donnan, W. W., Phelan, J. T., and others.
1956. The use of cylinder infiltrometers to determine the intake characteristics of irrigated soils. U.S. Dept. Agr. Agr. Res. Serv. ARS 41-7, 100 pp.

(5) Kelley, O. J., Hardman, J. A., and Jennings, D. S.
1947. A soil sampling machine for obtaining two-, three-, and four-inch-diameter cores of undisturbed soil to a depth of six feet. Soil Sci. Soc. Amer. Proc. 12:85-87.

(6) Kilmer, V. J. and Alexander, L. T.
1949. Methods of making mechanical analyses of soils. Soil Sci. 68:15-24.

(7) McNeal, B. L., and Sansoterra, T.
1964. The mineralogical examination of arid-land soils. Soil Sci. 97:367-375.

(8) Olsen, S. R., and Dean, L. A.
1965. Phosphorus. In Black, C. A., ed., Methods of Soil Analysis. American Society of Agronomy, Inc., Madison, Wis.

(9) Richards, L. A.
1947. Pressure membrane apparatus construction and use. Agr. Engin. 28:451.

(10) ______
1948. Porous plate apparatus for measuring moisture retention and transmission by soil. Soil Sci. 66:105-110.

(11) Soil Survey Staff.
[In press] Soil taxonomy of the national cooperative soil survey. U.S. Dept. Agr. Soil Conserv. Serv. Agr. Handb. 436.

APPENDIX TABLES

Table 1 -- The fraction percentages of clay for each profile soil sample.

Soil 1/	Depth	Fraction Percentage 2/						
		Mt	Mi	Q+F	Chl	Verm	Am	Kaol
	Inches							
Imperial sic	0-13	39	28	19	7	1	2	0
Holtville sic	0-10	35	28	18	6	8	2	0
	50-66	46	30	14	9	0	2	1
Holtville sic Taxadjunct	0-17	40	28	18	7	0	2	0
	35-72	42	28	14	8	2	2	0
Meloland 1	0-12	43	29	16	8	0	2	0
	18-26	45	29	14	8	2	2	0
	38-71	41	28	16	7	2	2	0
Indio 1	0-12	40	30	17	7	0	2	0
Indio vfsl Taxadjunct	0-13	43	28	15	8	1	2	0
	37-72	44	28	15	8	3	2	0
Averages		42	29	16	8	2	2	1

1/ sic = silty clay
1 = loam
vfsl = very fine sandy loam

2/ Mt = montmorillonite
Mi = mica
Q+F = quartz plus feldspars
Chl = chlorite
Verm = vermiculite
Am = amorphous minerals
Kaol = kaolinite

Table 2 -- Particle-size distribution analysis in percentages with size fraction in millimeters

Soil	Depth	Horizon	Very coarse sand (2-1)	Coarse sand (1-0.5)	Medium sand (0.5-0.25)	Fine sand (0.5-0.25)	Very fine sand (0.10-0.05)	Silt (0.05-0.002)	Clay (<0.002)	0.2-0.02	0.02-0.002	0.005-0.002	<0.001	<0.0002	Texture class 1/
	Inches														
Imperial	0-13	Ap	0.1	0.1	0.1	1.0	5.1	42.3	51.3	13.0	35.1	18.4	48.1	17.9	sic
sic	13-28	C1	.0	.0	.0	.0	.4	55.7	43.9	5.5	50.6	18.8	37.9	13.7	sic
	28-42	C2	.0	.0	.0	.1	.6	52.4	46.9	5.1	48.0	18.6	39.1	15.1	sic
Holtville	0-10	Ap	.1	.2	.2	2.7	9.0	42.2	45.6	24.5	28.9	13.4	38.5	14.7	sic
sic	10-22	C1	.0	.0	.1	2.2	7.1	40.0	50.6	17.8	31.2	16.1	42.5	16.3	c
	33-50	C3	.0	.0	.1	.5	1.8	84.8	12.8	46.5	40.4	5.8	11.5	--	sil
	50-66+	C4 & C5	.0	.1	.1	.6	19.2	72.4	7.6	80.4	11.6	3.5	7.5	--	sil
Holtville	0-17	Ap	.1	.1	.2	4.5	7.1	43.0	45.0	18.1	35.6	14.7	39.1	15.9	sic
sic	17-24	C1	.0	.0	.0	2.2	1.9	43.1	52.8	6.6	40.4	19.4	41.5	--	sic
Taxadjunct	24-35	C2	.0	.0	.1	1.7	3.8	67.6	26.8	29.9	43.0	10.2	22.7	--	sicl
	35-72+	C3	.0	.1	.1	18.7	61.5	13.9	5.7	89.2	3.5	1.8	5.7	--	lvfs
Meloland 1	0-12	Ap	.0	.1	.1	6.8	49.5	28.6	14.9	76.5	7.9	4.6	14.2	--	vfsl
	12-18	C1	.0	.1	.1	16.6	59.3	18.4	5.5	89.9	3.9	2.4	5.4	--	vfsl
	18-26	C2	.0	.1	.1	.5	9.1	75.2	15.0	57.9	26.8	5.9	13.8	--	sil
	26-38	C3	.1	.0	.0	.2	2.6	42.2	54.9	9.3	35.7	18.9	46.0	18.7	sic
	38-53	C4	.1	.0	.0	.1	1.6	46.2	52.0	8.4	39.5	19.5	43.3	18.1	sic
Indio 1	0-12	Ap	.0	.7	4.0	22.6	7.3	47.2	18.2	47.6	20.2	6.5	16.4	--	l
	12-30	C1	.0	.1	.3	2.1	5.6	79.4	12.5	63.5	22.8	5.4	11.4	--	sil
	44-58	C3	.0	.1	.1	.5	29.7	62.7	6.7	84.9	7.8	3.4	6.5	--	sil
Indio	0-13	Ap	.0	.1	.1	3.7	32.6	49.9	16.6	68.4	14.4	5.5	14.5	--	l
vfsl	13-27	C1	.0	.0	.1	1.3	33.3	55.7	9.6	78.8	11.2	3.8	8.7	--	sil
Taxadjunct	27-37	C2	.0	.0	.1	1.3	12.9	73.6	12.1	65.6	22.0	5.0	11.0	--	sil
	37-62	C3	.0	.1	.4	50.3	35.6	9.8	3.8	86.9	2.2	1.1	3.8	--	fs

1/ sic=silty clay
c=clay
sil=silt loam
sicl=silty clay loam

lvfs=loamy very fine sand
vfsl=very fine sandy loam
l=loam
fs=fine sand

Table 3 -- Atterburg constants and maximum compaction density at optimum moisture for major soils of Imperial Valley

Soil 1/	Depth	Atterberg constants: Liquid limit	Atterberg constants: Plastic limit	Atterberg constants: Plasticity index	Maximum compaction density at optimum moisture: Optimum moisture	Maximum compaction density at optimum moisture: Maximum density
	Inches	Percent	Percent	Number	Percent	Lb/ft^3
Imperial sic	0-13	58.0	22.7	35	16.0	112.0
	13-28	57.4	22.3	36	16.5	109.0
	28-42	58.3	23.0	35	16.0	111.0
Holtville sic	0-10	49.9	20.9	29	15.0	112.5
	10-22	58.0	21.4	37	10.0	110.0
	33-50	31.7	23.2	8	17.0	108.5
	50-66+	27.0	24.1	3	6.5	131.0
Holtville sic Taxadjunct	0-17	53.7	21.4	32	13.5	116.5
	17-24	59.9	21.8	38	15.0	114.0
	24-35	37.5	18.7	19	13.0	115.0
	35-72+	23.5	23.6	--	14.5	106.0
Meloland l	0-12	27.3	19.8	7	13.0	117.5
	12-18	24.5	24.3	--	15.0	108.0
	18-26	31.0	20.8	10	14.0	113.5
	26-38	65.8	21.7	44	15.5	110.0
	38-53	61.8	22.8	39	14.0	112.5
Indio l	0-12	27.6	20.6	7	10.0	121.5
	12-30	29.8	23.7	6	15.5	109.0
	44-58	28.9	22.2	7	14.0	112.5
Indio vfsl Taxadjunct	0-13	28.5	19.7	9	14.0	117.0
	13-27	26.0	21.6	4	15.0	114.0
	27-37	26.3	23.0	3	17.5	105.0
	37-62	23.5	23.4	--	6.0	105.5

1/ sic=silty clay
vfsl=very fine sandy loam
l=loam

Table 4 -- Soil moisture retention data for the major soils of Imperial Valley[1]

Soil [2]	Depth	Moisture content (dry weight basis) at specified suctions (bars)					
		0.1	0.3	1.0	2.0	5.0	15.0
	Inches	Percent	Percent	Percent	Percent	Percent	Percent
Imperial sic	0-13	41.1	32.9	26.4	26.0	20.7	18.6
	13-28	45.7	36.8	30.7	29.2	24.2	23.1
	28-42	46.2	37.7	30.9	29.1	24.7	22.8
Holtville sic	0-10	41.1	30.8	24.4	23.9	19.4	16.8
	10-22	41.4	33.3	27.6	26.5	22.6	19.4
	33-50	42.3	30.4	14.8	12.6	10.0	9.3
	50-66+	39.8	13.0	7.6	7.1	5.9	5.1
Holtville sic Taxadjunct	0-17	36.8	30.2	24.8	24.4	19.5	16.6
	17-24	43.9	34.5	29.6	28.0	23.1	20.2
	24-35	37.8	31.4	22.3	19.0	14.8	11.8
	35-72+	20.0	6.2	5.0	4.3	3.7	3.1
Meloland l	0-12	28.8	14.6	14.0	10.3	8.3	6.9
	12-18	20.4	6.7	5.2	5.0	4.2	3.8
	18-26	37.7	24.2	15.0	11.8	9.5	7.9
	26-38	45.8	37.6	31.2	30.3	24.5	21.9
	38-53	46.0	37.4	31.9	30.8	24.6	21.3
Indio l	0-12	30.2	19.6	13.0	12.8	10.3	8.3
	12-30	40.0	21.8	16.9	11.3	8.9	7.1
	44-58	37.6	10.6	10.7	6.4	5.3	4.7
Indio vfsl Taxadjunct	0-13	30.8	18.2	14.2	12.6	10.1	8.1
	13-27	32.8	14.8	10.6	8.7	7.1	5.8
	27-37	35.2	22.8	13.8	10.9	8.6	6.8
	37-62	9.0	5.3	4.3	3.5	3.1	2.4

1/ Determined on artifacts of crushed, sieved samples.
2/ sic=silty clay
vfsl=very fine sandy loam
l=loam

Table 5 -- The average bulk density and standard deviation (four replications) at field moisture conditions for the major Imperial Valley soils

Soil 1/	Depth	Bulk density
	Inches	g/cm^3
Imperial sic	0-12	1.37 ± 0.12
	12-24	1.52 ± .03
	24-36	1.55 ± .06
	36-48	1.55 ± .08
	48-60	1.52 ± .02
	60-72	1.56 ± .03
Holtville sic	0-12	1.40 ± .06
	12-24	1.51 ± .01
	24-36	1.50 ± .01
	36-48	1.46 ± .02
	48-60	1.48 ± .03
	60-72	1.50 ± .07
Holtville sic Taxadjunct	0-6	1.10 ± .06
	6-12	1.43 ± .05
	12-18	1.50 ± .03
	18-24	1.50 ± .04
	24-30	1.56 ± .04
	30-36	1.66 ± .06
	36-42	1.61 ± .04
	42-48	1.60 ± .01
	48-54	1.66 ± .04
	54-60	1.69 ± .02
Meloland l	0-6	1.29 ± .16
	6-12	1.42 ± .08
	12-18	1.46 ± .04
	18-24	1.41 ± .06
	24-30	1.41 ± .09
	30-36	1.44 ± .03
	36-42	1.48 ± .03
	42-48	1.59 ± .02
	48-54	1.55 ± .05
	54-60	1.58 ± .05
Indio l	0-12	1.63 ± .06
	12-24	1.48 ± .03
	24-36	1.46 ± .03
	36-48	1.53 ± .02
	48-60	1.59 ± .06
	60-72	1.64 ± .04

See footnote at end of table

Table 5 -- continued

Soil 1/	Depth	Bulk density
	Inches	g/cm^3
Indio vfsl Taxadjunct	0-6	1.39 ± .08
	6-12	1.49 ± .02
	12-18	1.52 ± .03
	18-24	1.58 ± .01
	24-30	1.60 ± .03
	30-36	1.66 ± .04
	36-42	1.67 ± .04
	42-48	1.74 ± .03
	48-54	1.70 ± .02
	54-60	1.68 ± .11

1/ sic = silty clay
vfsl = very fine sandy loam
l = loam

Table 6 -- The average infiltration rate (for an 8-hour period), standard deviation, and coefficient of variation (six replications) for the major Imperial Valley soils

Soil 1/	Infiltration rate	Coefficient of variation
	In/hr	Percent
Imperial sic	0.051 ± 0.010	19.6
Holtville sic	.092 ± .039	42.4
Holtville sic Taxadjunct	.396 ± .318	80.3
Meloland l	.315 ± .083	26.3
Indio l	.208 ± .116	55.8
Indio vfsl Taxadjunct	.267 ± .163	60.9

1/ sic = silty clay
vfsl = very fine sandy loam
l = loam

Table 7 -- Saturation extract determinations

Soil[1]	Depth	Electrical Conductivity	Cations					Anions					Sodium Adsorption Ratio (SAR)
			Ca^{++}	Mg^{++}	Na^{+}	K^{+}	Total	$CO_3^{=}$	HCO_3^{-}	$SO_4^{=}$	Cl^{-}	Total	
	Inches	Mmhos/cm	Meq/l	Meq/l	Meq/l	Meq/l	Meq/l	Meq/l	Meq/l	Meq/l	Meq/l	Meq/l	
Imperial sic	0-13	4.9	22.90	11.87	24.0	0.76	59.53	0	8.56	38.52	19.26	66.34	5.8
	13-28	9.0	24.80	21.31	78.0	.40	124.51	0	2.97	104.10	24.01	131.08	16.2
	28-42	12.0	35.02	15.74	112.0	.70	163.46	0	2.90	83.28	67.86	154.04	22.2
Holtville sic	0-10	6.8	30.50	19.64	38.0	1.70	89.84	0	6.53	58.30	26.10	90.93	7.6
	10-22	7.4	27.80	21.28	68.0	.90	117.98	0	3.63	80.68	23.49	107.80	13.7
	33-50	13.0	35.80	22.82	120.0	.56	179.18	0	4.21	74.95	82.48	161.64	22.2
	50-66+	9.2	30.60	19.01	48.0	.88	98.49	0	6.09	41.64	60.65	108.38	9.6
Holtville sic Taxadjunct	0-17	5.0	24.25	12.03	30.0	.96	67.24	0	7.54	48.41	16.96	72.91	7.0
	17-24	5.0	23.83	15.58	26.0	.72	66.13	0	5.51	60.38	9.92	75.81	5.9
	24-35	3.3	10.99	6.41	15.2	.48	33.08	0	5.08	28.11	12.27	45.46	5.2
	35-72+	4.8	12.00	7.50	28.8	.72	49.02	0	5.95	34.35	12.53	52.83	9.2
Meloland l	0-12	7.0	32.38	19.72	32.0	.56	84.66	0	3.77	52.57	29.49	85.83	6.3
	12-18	2.8	9.80	1.44	11.2	.26	22.70	0	8.85	14.57	8.35	31.77	4.7
	18-26	7.0	27.54	22.27	45.0	.28	95.09	0	2.90	87.44	21.92	112.26	9.0
	26-38	7.4	24.75	17.01	50.0	.40	92.16	0	6.53	94.73	13.05	114.31	10.9
	38-53	8.0	20.56	19.90	62.0	.54	103.00	0	5.80	99.42	15.66	120.88	13.8
Indio l	0-12	5.0	21.43	15.09	20.4	1.40	58.32	0	8.70	33.31	21.14	63.15	4.8
	12-30	7.0	31.92	19.99	34.8	.89	87.60	0	4.21	64.54	33.15	101.90	6.8
	44-58	5.6	23.60	11.80	24.8	1.40	61.60	0	8.56	32.27	21.92	62.75	5.9
Indio sic Taxadjunct	0-13	19.0	26.85	27.96	148.0	1.28	204.09	0	9.43	122.84	83.52	215.79	28.3
	13-27	17.0	27.35	28.16	152.0	.46	207.97	0	7.91	116.59	91.35	215.85	28.8
	27-37	12.0	20.56	15.81	122.0	.46	158.83	0	8.12	122.84	36.02	166.98	28.6
	37-62	13.0	10.94	16.78	126.0	.30	154.02	0	14.51	68.70	64.63	147.84	33.8

[1] sic = silty clay
l = loam

Table 8 -- Soil determinations

Soil [1/]	Depth	Saturation	pH of saturated soil	Cation exchange capacity	Exchangeable cation percentages Na^+	Exchangeable cation percentages K^+	Gypsum	Calcium carbonate equivalent $\%CaCO_3$	Free iron oxides $\%Fe_2O_3$	Total surface area
	Inches	Percent		Meq/100g			Meq/100g			M^2/g
Imperial sic	0-13	76.9	7.6	34.2	14	4	1.2	12.39	1.18	204.82
	13-28	77.2	7.9	32.0	22	2	7.3	14.34	1.36	194.75
	28-42	76.2	7.9	33.8	15	3	2.2	14.32	1.30	195.01
Holtville sic	0-10	66.5	7.6	27.5	12	5	2.6	11.77	1.14	172.28
	10-22	77.8	7.7	30.5	9	3	5.4	11.38	1.12	202.47
	33-50	42.1	7.7	16.0	11	3	2.2	16.69	.84	102.75
	50-66+	21.6	7.7	10.2	17	4	.2	14.08	.69	61.42
Holtville sic Taxadjunct	0-17	70.0	7.7	29.5	21	4	.6	12.42	1.04	172.78
	17-24	83.0	7.7	34.8	17	3	1.4	12.18	1.01	216.42
	24-35	54.7	7.8	24.2	27	3	.4	14.82	.84	140.84
	35-72+	17.2	7.7	7.4	30	5	.0	7.90	.46	36.42
Meloland l	0-12	40.5	7.6	13.2	15	3	.4	9.55	.64	65.24
	12-18	20.6	7.6	7.2	19	3	.1	8.74	.44	38.66
	18-26	41.2	7.6	15.6	19	2	1.8	15.63	.72	90.23
	26-38	93.2	7.7	38.0	16	2	5.6	12.13	1.09	216.08
	38-53	88.1	7.9	35.2	18	2	5.7	13.08	1.15	214.10
Indio l	0-12	35.5	7.6	15.5	30	6	.2	11.14	.73	90.15
	12-30	39.9	7.7	15.0	11	3	.4	14.88	.86	78.80
	44-58	19.8	7.9	9.8	19	3	.2	13.82	.56	54.39
Indio sic Taxadjunct	0-13	43.1	7.9	14.4	26	4	5.5	11.56	.64	82.88
	13-27	38.0	8.2	12.0	20	5	5.6	12.20	.60	66.36
	27-37	44.3	8.1	14.6	16	4	1.9	13.98	.68	81.31
	37-62	13.2	8.2	6.5	23	3	.0	6.39	.40	26.24

1/ sic = silty clay
l = loam

Table 9 -- Organic nitrogen, organic carbon and organic matter

Soil 1/	Depth	Organic nitrogen 2/	Organic carbon 3/	Organic matter 4/
	Inches	P/m	Percent	Percent
Imperial sic	0-13	784	0.69	1.19
	13-28	378	.30	.52
	28-42	374	.28	.49
Holtville sic	0-10	746	.82	1.41
	10-22	488	.43	.74
	35-50	232	.30	.51
	50-66+	126	.14	.24
Holtville sic Taxadjunct	0-17	558	.52	.90
	17-24	318	.22	.38
	24-35	238	.20	.34
	35-72+	52	.05	.08
Meloland l	0-12	476	.42	.73
	12-17	91	.08	.13
	17-26	231	.23	.40
	26-38	354	.26	.44
	38-53	374	.26	.44
Indio l	0-12	498	.48	.82
	12-30	310	.44	.76
	44-58	110	.12	.20
Indio vfsl Taxadjunct	0-13	354	.31	.54
	13-27	134	.11	.19
	27-37	136	.13	.22
	37-62	32	.03	.06

1/ sic = silty clay
vfsl = very fine sandy loam
l = loam

2/ Kjeldahl method.

3/ Calculated from organic matter: Organic carbon = percentage of organic matter/1.72.

4/ Walkley-Black method: Percentage of organic matter = (meq $K_2Cr_2O_7$) (0.69)/g soil.

Table 10 -- Phosphorus Analysis of Soils

Soil 1/	Depth	Total-P (mineral and organic)	Phosphorus fractionation analysis					0.5N $NaHCO_3$ extractable-P
			Organic-P	Aluminum-P	Iron-P	Calcium-P	Other-P	
	Inches	P/m	P/m	P/m	P/m	P/m	P/m	P/m
Imperial sic	0-13	875	33	64	1	610	167	20
	13-28	760	8	18	1	574	159	4
	28-42	772	20	20	1	590	141	9
Holtville sic	0-10	818	45	59	2	497	215	16
	10-22	712	20	23	1	497	171	4
	33-50	712	0	11	1	573	127	6
	50-66+	625	42	10	1	542	30	4
Holtville sic Taxadjunct	0-17	835	8	51	0	527	249	15
	17-24	742	20	27	0	497	198	3
	24-35	733	8	15	0	454	256	1
	35-72+	438	8	11	0	250	169	3
Meloland l	0-12	612	43	59	1	401	108	11
	12-18	524	29	8	2	376	109	10
	18-26	673	8	11	0	454	200	2
	26-38	732	45	18	0	401	268	3
	38-53	781	68	20	0	590	103	6
Indio l	0-12	712	32	69	2	512	97	30
	12-30	692	20	13	1	527	131	5
	44-58	594	19	11	1	441	122	3
Indio vfsl Taxadjunct	0-13	712	32	34	0	512	134	18
	13-27	675	0	11	0	497	167	1
	27-37	663	20	11	0	558	74	2
	37-62	356	46	11	0	282	17	2

1/ sic = silty clay
vfsl = very fine sandy loam
l = loam

Table 11 -- Linear regression analysis of clay content (<2μ) as related to a given soil property

Soil Property	Slope	Intercept	Correlation coefficient	Significance level 1/
Physical measurements				
Moisture retention (bars):				
0.1	0.3339	27.2383	0.682	S **
.3	.5044	10.5520	.885	S **
1.0	.4627	6.1857	.957	S **
2.0	.4871	3.7812	.982	S **
5.0	.4004	2.9593	.982	S **
15.0	.3450	2.4020	.993	S **
Soil bulk density (g/cm^3)	------	-------	-.384	NS
Atterburg constants:				
Liquid limit (percent)	.7881	18.8934	.984	S **
Plastic limit (percent)	------	-------	-.205	NS
Plastic index (No.)	.8066	-3.6802	.989	S **
Optimum moisture content (percent)	------	-------	.261	NS
Maximum density (lb/ft^3)	------	-------	-.029	NS
Chemical measurements				
Saturation extract determinations:				
Electrical conductivity (mmhos/cm)	------	-------	-.227	NS
Total cations (meq/l)	------	-------	-.113	NS
Total anions (meq/l)	------	-------	-.099	NS
Sodium adsorption ratio	------	-------	-.220	NS
Soil determinations:				
Saturation (percent)	1.2530	18.0602	0.969	S **
Cation exchange capacity (meq/100g)	.5460	6.2440	.984	S **
Exchangeable sodium (percent)	------	-------	-.324	NS
Exchangeable potassium (percent)	------	-------	-.266	NS
Gypsum (meq/100 g)	.0586	.6557	.480	S *
Calcium carbonate equivalent (percent $CaCO_3$)	------	-------	.178	NS
Free iron oxides (percent Fe_2O_3)	.0134	.4924	.908	S **
Total surface area (m^2/g)	3.4573	30.1160	.986	S **
Organic matter determinations:				
Organic matter (percent)	.0097	.2537	.539	S **
Organic nitrogen (p/m)	7.5022	121.0291	.704	S **
Phosphorous analysis:				
Extractable-P (p/m)	------	-------	.160	NS
Total-P (p/m)	4.6842	560.2998	.748	S **

1/ Significance level with 23 samples each.

S = significant correlation.
* = 5-percent level.
** = 1-percent level.
NS = nonsignificant correlation

Table 12 -- Linear regression analysis of soil saturation percentage as related to given soil property

Soil property	Slope	Intercept	Correlation coefficient	Significance level 1/
Physical measurements				
Moisture retention (bars):				
0.1	0.2860	21.4250	0.756	S **
.3	.4143	2.6811	.940	S **
1.0	.3664	- .3348	.980	S **
2.0	.3774	- 2.6589	.984	S **
5.0	.3085	- 2.2436	.978	S **
15.0	.2937	- 2.0017	.987	S **
Soil bulk density (g/cm^3)	------	-------	- .401	NS
Atterburg constants:				
Liquid limit (percent)	.5926	9.4019	.957	S **
Plastic limit (percent)	------	--------	- .240	NS
Plastic index (No.)	.6083	-13.4855	.965	S **
Optimum moisture content (percent)	------	--------	.386	NS
Maximum density (lb/ft^3)	------	-------	- .070	NS
Chemical measurements				
Saturation extract determinations:				
Electrical conductivity (mmhos/cm)	------	--------	- .114	NS
Total cations (meq/l)	------	-------	.012	NS
Total anions (meq/l)	------	--------	.043	NS
Sodium adsorption ratio	------	--------	- .129	NS
Soil determinations:				
Cation exchange capacity (meq/100 g)	0.4220	-0.9218	0.984	S **
Exchangeable sodium (percent)	------	------	- .365	NS
Exchangeable potassium (percent)	------	------	- .348	NS
Gypsum (meq/100 g)	.0551	- .6164	.583	S **
Calcium carbonate equivalent (percent $CaCO_3$)	------	------	.309	NS
Free iron oxides (percent Fe_2O_3)	.0104	.3149	.912	S **
Total surface area (m^2/g)	2.6574	-14.4842	.980	S **
Organic matter determinations:				
Organic matter (percent)	.0068	.1590	.493	S *
Organic nitrogen (p/m)	5.3865	43.7488	.654	S **
Phosphorous analysis:				
Extractable-P (p/m)	------	------	.076	NS
Total-P (p/m)	3.8288	488.1472	.791	S **

1/ Significance level with 23 samples each.

S = significant correlation
* = 5-percent level
** = 1-percent level
NS = nonsignificant correlation

Table 13 -- Linear regression analysis of the sodium adsorption ratio as related to exchangeable sodium percentage and pH

Soil property	Slope	Intercept	Correlation coefficient	Significance level 1/
Exchangeable sodium (percent) (ESP)	-----	--------	0.021	NS
pH	0.0167	7.5576	.820	S **

1/ Significance level with 23 samples each.

NS = nonsignificant correlation
S = significant correlation
** = 1-percent level

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ALFALFA WATER STRESS MANAGEMENT DURING SUMMER IN IMPERIAL VALLEY FOR WATER CONSERVATION

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DECEMBER 1994

DESERT RESEARCH AND EXTENSION CENTER
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FINAL REPORT 1994

ALFALFA WATER STRESS MANAGEMENT DURING SUMMER MONTHS IN IMPERIAL VALLEY FOR WATER CONSERVATION

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THE METROPOLITAN WATER DISTRICT OF SOUTHERN CALIFORNIA
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THE IMPERIAL VALLEY CONSERVATION RESEARCH CENTER COMMITTEE

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ABSTRACT

The objectives of this study were to determine the amount of water reduction which can be tolerated by alfalfa during the summer, the consequent soil salinity increase and yield reduction and to determine if seven cultivars of alfalfa differed in their ability to withstand periods of drought.

Four irrigation treatments were applied to seven alfalfa varieties in 1991, 1992 and 1993 as follows:

Irrigation treatments imposed during the summer months

Irrigation Treatment	Number of irrigations July	August	September
Optimum Check	3	2	2
Minimal stress	3	1	1
Short stress	3	0	0
Long stress	0	0	0

WATER SAVING AND YIELD REDUCTION

A comparison of the three drier treatments to the optimum.

Irrigation treatments compared to Optimum	Number of irrigations saved per year	Average Yield Reduction tons/acre/year			Average Water Saved acre-feet/acre/year		
		1 Year	1+2 Years	1+2+3 Years	1 Year	1+2 Years	1+2+3 Years
Optimum - minimum	2	0.39	0.54	0.66	0.27	0.16	0.17
Optimum - short	4	1.79	1.60	1.68	1.30	1.25	1.17
Optimum - long	7	2.86	2.34	2.31	2.17	2.08	2.04

VALUE OF WATER

Assuming a value of $100/ton for alfalfa the water value per acre-foot saved by the minimum, short and long treatments were:

Irrigation treatment	Average value of each acre-foot saved ($/acre-foot) 1st year	1st & 2nd years	1st,2nd & 3ed years
Minimum	144	338	388
Short	138	128	144
Long	132	113	113

The soil saturation extracts corrected to field capacity in each irrigation treatment area over the three years that the irrigation treatments were applied, the leaching irrigation afterward and the growth of a subsequent sudan grass crop, is shown in the following table:

Soil profile average saturation extracts (dS/m) at field capacity during and after the alfalfa experiment.

Period	Date	Opt	Min	Short	Long	Sig	Profile average
Start	1/2/91	6.3	6.4	6.5	6.3	n.s.	6.4
End 1st year	10/16/91	6.3	6.8	8.4	8.5	n.s.	7.5
End 2nd year	10/20/92	6.1	6.1	7.9	8.2	5%	7.1
End 3ed year	10/19/93	6.0	6.0	8.3	7.6	n.s.	7.0
Leaching	3/2/94	6.0	6.1	7.2	7.5	n.s.	6.7
Sudan cut	6/21/94	5.4	5.4	6.6	6.2	n.s.	5.9
Sudan cut	8/10/94	5.7	6.4	6.4	6.0	n.s.	6.1

It was concluded that the optimum treatment did not accumulate a salinity residual. The minimum treatment had a salinity increase the first year but then corrected during the next two years. The short and long treatments had soil salinity increases during the treatments that was improved but not corrected by a leaching irrigation after the alfalfa was removed. The soil salinity residual from all of the treatments was removed by growing a sudan crop following the alfalfa crop.

The three year total dry weight yields of cultivars showed a significant difference in the driest treatment. Highest yields were in the group of UC Cibola, CUF 101, and UC 150. The intermediate group contained Moapa 69, Wilson, and Mesilla. The lowest yield was from Dofari.

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ALFALFA WATER STRESS MANAGEMENT DURING SUMMER MONTHS IN IMPERIAL VALLEY FOR WATER CONSERVATION

Frank E. Robinson[1]

This project addressed the opportunity of making agricultural water in the Imperial Valley available for urban uses during times of urban water shortage. It is based on the premise that agricultural lands need not be removed from production and that no significant shift in crop pattern will need to be adopted.

Alfalfa is a major crop in the Imperial Valley and is also a high water user. Crop stressing with concurrent reduction in yields is one strategy for reducing water application to alfalfa. Although water stressing may appear to be a counter-productive practice, it may be effective under certain conditions. The relationship between alfalfa yield and water use is not constant during the year. Using information summarized in the University of California Leaflet 21097 (Lehman 1979) on alfalfa production in the low desert valleys of California, the ratio of yield to water use was determined for each month. Lowest ratios of yield to water use are found from July to November. Reportedly, some years ago, the practice in the Imperial Valley was to withhold irrigation during August and September to withstand soil pathogen attack during this period. Stand survival was the primary concern. Return to this practice might result in significant water savings with minimal yield reduction. A single 4.8-inch irrigation on Imperial Valley's 193,000 (Birdsall, 1991) acres of alfalfa requires 77,200 acre-feet of water. For each irrigation eliminated, this much water would be "saved." The cost of such irrigation "saving" to the alfalfa producer is unknown and is the basis for this research report.

OBJECTIVES

The objectives of this experiment are to determine the amount of irrigation water reduction during the summer which can be tolerated by alfalfa; to examine the economics of irrigation reduction on alfalfa; and to determine if alfalfa cultivars and germ plasm CUF 101, Cibola, Moapa 69, UC-150, Mesilla, Wilson and Dofari differ in their ability to withstand periods of drought during the summer in Imperial Valley. Dr Larry R. Teuber[2] will provide carbohydrate, nitrogen, fiber and mineral composition analysis for this study in an appendix at a later date. These data were used by Dr Robert S. Loomis[3] in the growth model "ALFALFA" to simulate changes induced by the irrigation treatments.

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1. Frank E. Robinson, Water Scientist Emeritus, University of California, Davis and Desert Research and Extension Center.
2. Larry R. Teuber, Associate Professor of Agronomy, University of California, Davis.
3. Robert S. Loomis, Professor of Agronomy Emeritus, University of California, Davis.

MATERIALS AND METHODS

PLOT LAYOUT

Soil in the experimental area on the Desert Research and Extension Center is a Holtville clayey over loamy, montmorillonitic (calcarious), hyperthermic Typic Torrifluvent. Mechanical analysis of the irrigation plots was done in 15 cm (6 in.) increments to 1.2 m (4 feet). The west side of the plot area has a clay layer extending into the 60 to 90 cm (2 to 3 foot) depth overlying a sandy clay while the east side has a clay layer to only the 30 to 60 cm (1 to 2 foot) depth above a sandy clay sublayer. Tile drains are at the 1.80 m (6 foot) depth and run diagonally across the area. A water table that fluctuates around the 170 cm (6 foot) depth was monitored from the center of each replication.

The experiment consisted of four irrigation treatments with three replications north to south in three separate parallel randomized block experiments side by side east to west (Figure 1). The three randomized block experiments were placed to isolate the different soil conditions in the east to west direction. The border check irrigation system had borders 18.3 m (60 feet) apart and were 83 m (270 feet) long. Because the soils developed deep cracks as they dried, unplanted strips were left on either side of the planted alfalfa plots and irrigated with the alfalfa. Keeping the unplanted strips moist kept them from cracking and prevented water movement from one irrigation treatment to the next. The 3.66 m (12 foot) unplanted strip was the size of the disk that was used to remove weeds from the unplanted area when the alfalfa plots were dried for cutting. The alfalfa plots were in a strip 9.1 x 83m (30 x 271 feet). Plots inside the strip were in two columns of 1.5 x 5.5 m (5 x 18 feet) plots, a 30 cm (1 foot) strip was maintained between and on either side of the columns. A 60 cm (2 foot) space was maintained between plots in the column. On each side of the plots was a 2.6 m (8.5 foot) strip of CUF 101. There were three sets of the 7 varieties, one for each soil condition designated as west, center, and east. The irrigation treatments are shown in table 1. The irrigation treatment layout is shown in Figure 1 and the cultivar sequence in Figure 2.

IRRIGATION TREATMENTS

Table 1. Irrigation treatments imposed during the summer months.

Irrigation Treatment	Number of irrigations July	August	September
Optimum check	3	2	2
Minimal stress	3	1	1
Short stress	3	0	0
Long stress	0	0	0

FIELD PLOT LAYOUT

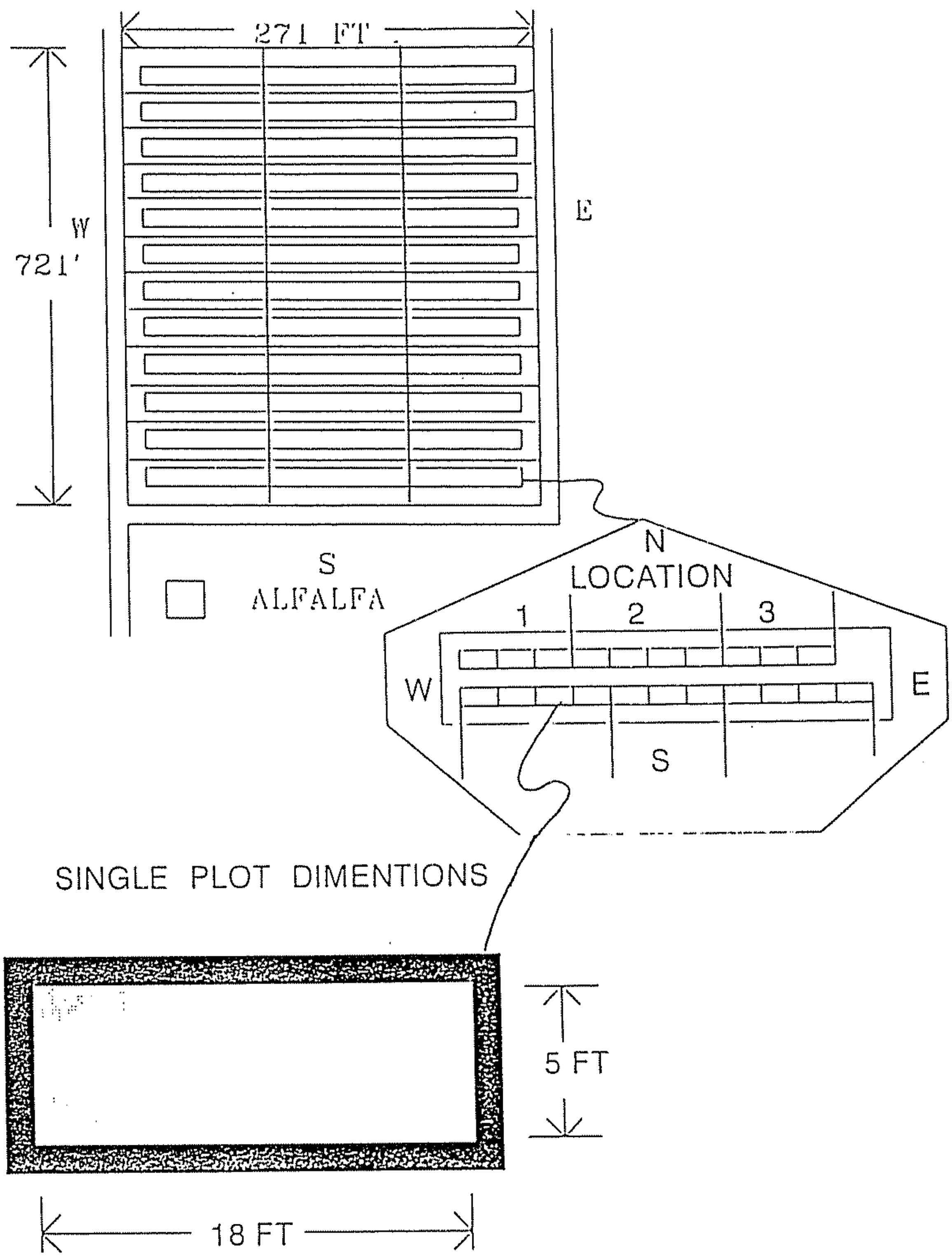


Figure 1. Lower, single cultivar plot; center, irrigation treatment plot showing three locations with seven cultivar plots in each; top, 4.5 acre field plot showing 12 irrigation plots.

NORTH END OF PLOT AREA

WEST LOCATION				CENTER LOCATION			EAST LOCATION				IRRIGATION TREATMENT
REPLICATION 1											
101	CIB	M69	MES	101	DOF	WIL	DOF	101	CIB	-o-	MINIMUM
150	MES	WIL	DOF	150	CIB	M69	150	M69	MES	WIL	
DOF	101	WIL	M69	DOF	CIB	MES	101	M69	CIB	DOF	OPTIMUM
CIB	150	MES	150	WIL	M69	101	MES	150	WIL	-o-	
M69	MES	WIL	WIL	101	150	DOF	MES	CIB	DOF	-o-	SHORT
150	101	DOF	CIB	MES	M69	CIB	WIL	101	150	M69	
101	DOF	150	M69	CIB	WIL	150	DOF	MES	101	150	LONG
MES	CIB	WIL	MES	DOF	101	M69	WIL	CIB	M69	-o-	
REPLICATION 2											
DOF	101	MES	DOF	M69	CIB	150	M69	DOF	MES	-o-	LONG
CIB	150	M69	WIL	101	MES	WIL	WIL	CIB	150	101	
DOF	M69	CIB	150	WIL	101	MES	101	150	DOF	WIL	SHORT
101	WIL	MES	DOF	CIB	M69	150	CIB	MES	M69	-o-	
150	WIL	101	WIL	M69	150	CIB	101	DOF	MES	-o-	OPTIMUM
CIB	MES	M69	DOF	MES	101	DOF	150	M69	WIL	CIB	
DOF	150	CIB	MES	DOF	M69	MES	CIB	WIL	101	M69	MINIMUM
M69	WIL	101	150	WIL	CIB	101	DOF	MES	150	-o-	
REPLICATION 3											
WIL	150	DOF	DOF	CIB	WIL	M69	DOF	CIB	MES	-o-	MINIMUM
CIB	M69	MES	101	150	101	MES	M69	101	WIL	150	
DOF	150	WIL	CIB	MES	150	CIB	MES	CIB	M69	101	OPTIMUM
101	MES	M69	WIL	M69	DOF	101	DOF	150	WIL	-o-	
WIL	DOF	101	CIB	DOF	M69	WIL	DOF	150	CIB	-o-	SHORT
M69	CIB	150	MES	101	MES	150	101	M69	WIL	MES	
MES	150	M69	DOF	150	WIL	101	150	CIB	MES	WIL	LONG
WIL	101	CIB	M69	DOF	CIB	MES	M69	DOF	101	-o-	

SOUTH END OF PLOT AREA

CULTIVAR KEY

CIB = UC CIBOLA	MES = MESILLA	WIL = WILSON
101 = CUF 101	M69 = MOAPA 69	-o- = no plot
DOF = DOFARI	150 = UC 150	

Figure 2. Diagram of cultivar plot sequence in irrigation treatments.

The soil moisture was monitored from neutron access tubes with measurements before and after irrigation and before and after cutting. Tubes were placed 1.2 m (4 feet) deep and read in 15 cm (6 inch) increments. The top 15 cm (6 inches) was determined with gravimetric soil samples. In addition, neutron access tubes were placed in the unplanted area in each replication to a depth of 1.9 m (6.5 feet). They were in one treatment receiving no irrigation for at least two months adjacent to one receiving water during every irrigation. A piezometer was placed one meter from the tube in the unplanted area to measure the water table depth, chloride concentration and electrical conductivity. A Stevens meter recording the water table in the field next to the experimental area was also monitored. An analysis of variance was performed on the change in the profile average soil moisture content for each successive neutron soil water measurement. Changes in soil moisture were compared to CIMIS (California Irrigation Management Information System) reference evapotranspiration (ETr) calculated over a short grass on the Center approximately 400m (1200 feet) from the experimental plots.

Soil salinity was measured from saturation extracts of samples taken from 30 cm (one foot) increments to 120 cm (four feet) of depth on the east and west set of plots for all treatments. Samples were taken on January 2, June 4, September 4, and October 16, 1991. Analysis of variance was performed on the profile average salinity from successive measurements of each of the four depths and the profile average.

In 1992 chloride content and electrical conductivity of soil saturation extracts in the border next to the CUF 101 plots were determined in March, June, August and October . In 1993 these measurements were taken in February, June, August and October.

ALFALFA YIELD AND MEASUREMENTS

Alfalfa plots were planted and irrigated on October 23, 1990. Treflan, a preplant herbicide, was sprayed and disk harrowed prior to planting. In March 1991 plots were cut to allow the alfalfa to outgrow a weed problem. A few larger weeds were treated with roundup. The first harvest on April 17, 1991 was followed in the separate irrigation treatments as shown in Table 2.

Table 2. Harvests in four irrigation treatment plots in three years.

Irrigation Treatment	1991	1992	1993
Optimum Check	8	9	9
Minimal stress	8	9	9
Short stress	6	7	7
Long stress	5	6	6

The short and long stress treatments were not harvested during the time they were not irrigated. This allowed the standing stalks to shade the crowns from direct solar radiation. Stand data were obtained to evaluate this practice.

Stand counts were taken after harvest in May, July, and October each year in each variety plot. The center of each count area was marked with an iron spike and located with a metal detector. A 0.1 m hoop was centered on the spike to locate the same area for each successive count. Analysis of variance was performed on the counts. Degree of cover of each plot was rated periodically on a scale of one to ten prior to cutting and analyzed by analysis of variance. Whitefly damage was assessed on a scale of 1 to 5 on October 21, 1991. Weed numbers per plot were recorded after the termination of the irrigation treatments in 1991.

For each harvest, height measurements were taken prior to cutting. Root samples were taken from the CUF 101 plots to determine carbohydrate accumulation in April, June, July, August, September and October. Sub-samples were taken from the CUF 101 plots for nitrogen, fiber, and mineral composition analysis. The green weight, percentage dry weight, and dry weight yield were measured for each of the 252 plots for each harvest. When four of the irrigation treatments were harvested the analysis of variance was done with four treatments, when three were harvested the analysis was with three treatments, and two with two treatments.

RESULTS AND DISCUSSION

The depth of the water table recorded in the short stress treatment plot from a 5 cm diameter well in each of the three replications is presented in Figure 3. Simultaneously the depth to the water table in an adjacent field was recorded on a Stephens meter. The peak depths to the water table recorded on the Stephens meter during irrigation in the adjacent field did not produce response peaks in the water table in the experimental plot area.

After the differential irrigation treatment had been completed in October of each year the amount of water replaced in the unplanted strips between the treatment plots was measured as shown in Figure 4. There was less than 1 cm (0.25 inch) loss from any 15 cm (six inch) layer below the top. The loss of water was primarily in the top 15 cm (6 inches) which had cracked to a visual depth of only 5 cm (2 inches). This indicated the effectiveness of the wet unplanted barrier between treatments that had prevented deep cracking and subsequent water movement between plots.

A summary of the water extracted by the alfalfa is presented in Table 3. These data show: 1) the CIMIS ETr over a short grass for each interval, 2) the water extracted during the same interval between irrigations, 3) the water replaced at the end of the interval as measured by the neutron probe and gravimetric soil sample and 4) the ratio of the extracted water to the Etr of

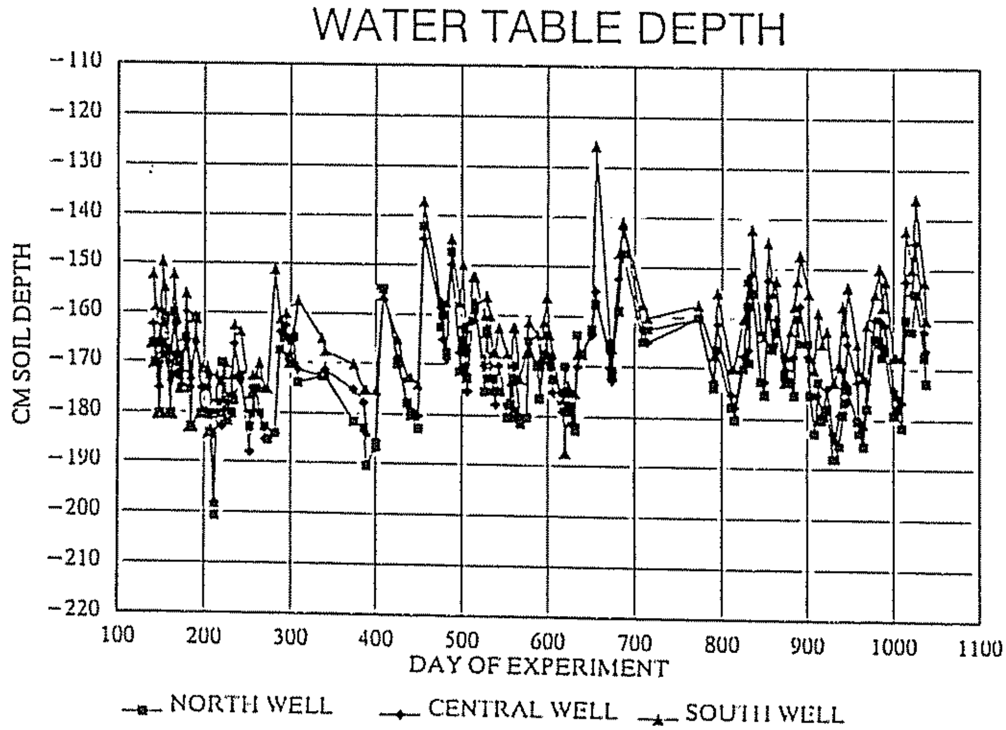


Figure 3. Depth of water in three sample wells on the alfalfa plots.

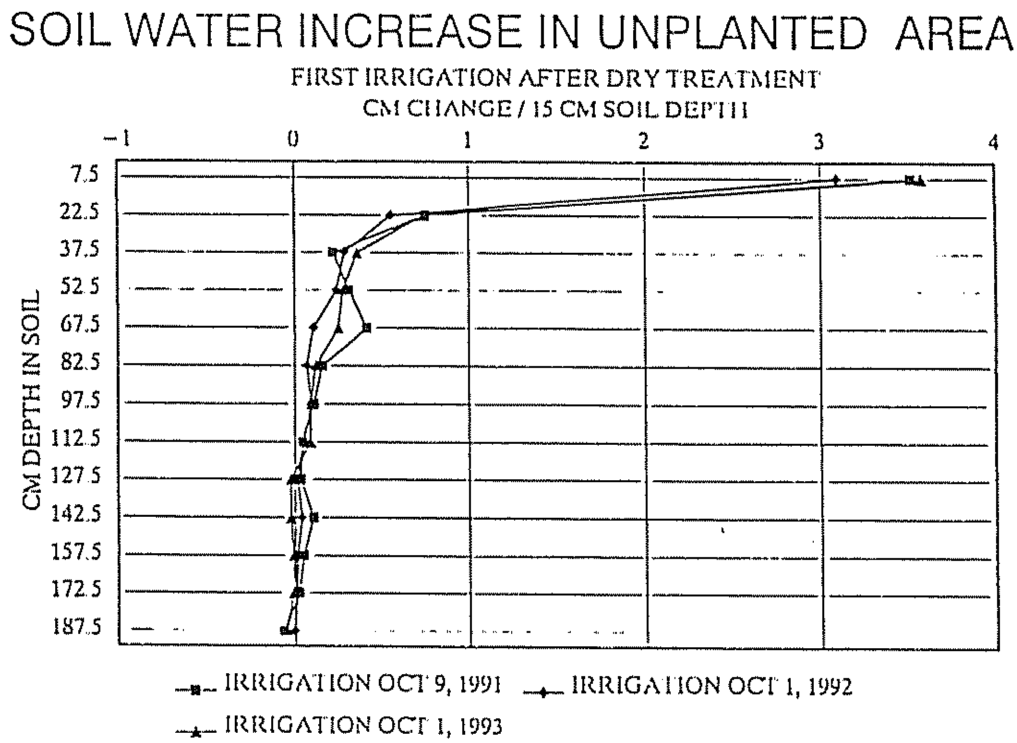


Figure 4. Soil water increase in unplanted area.

Table 3. CIMIS ETr, water extraction from 122 cm soil profile during intervals between irrigations, water replacement at the end of the interval and ratio of water extracted to CIMIS ETr in 1991.

		Optimum Stress			Minimum Stress		
Interval Dates	ETr	Water Extract	Water Replaced	Extract ETr Ratio	Water Extract	Water Replaced	Extract ETr Ratio
	mm	mm	mm	-----	mm	mm	-----
3/18-2/5	135.74	-96.47	97.54	0.71	-96.47	97.54	0.71
4/8-3/19	97.38	-77.28	68.99	0.79	-77.28	68.99	0.79
4/29-4/9	115.72	-88.61	95.30	0.75*	-85.71	95.30	0.75*
5/13-4/30	88.78	-86.54	89.98	0.97	-86.54	89.98	0.97
5/28-14	102.50	-103.04	98.88	1.01*	-103.04	98.88	1.01*
6/10-5/29	79.79	-92.44	92.18	1.16	-92.44	92.18	1.16
6/24-6/11	92.48	-75.88	76.55	0.82*	-75.88	76.55	0.82*
7/3-6/25	66.22	-82.64	61.05	1.24	-82.64	62.03	1.24
7/22-7/5	118.94	-88.48	98.42	0.74*	-85.50	93.36	0.72*
7/30-7/23	54.70	-59.03	60.14	1.08	-51.12	48.01	0.93
8/19-7/31	133.30	-99.83	121.25	0.75*	-94.93	111.39	0.71*
8/29-8/20	63.66	-63.71	53.06	1.00			
9/9-8/30	59.26	-57.31	65.55	0.97	-111.24	103.31	0.86
9/25-9/10	81.81	-84.05	69.32	1.03*			
10/8-9/26	61.49	-45.92	54.85	0.75	-109.43	105.37	0.76*
10/29-10/9	79.95	-62.32	65.96	0.83*	-61.59	60.30	0.77*
Total	1431.67	-1263.5	1269.02	0.88	-1214.59	1203.19	0.85
		Short Stress			Long Stress		
3/18-2/5	135.74	-96.47	97.54	0.71	-96.47	97.54	0.71
4/8-3/19	97.38	-77.28	68.99	0.79	-77.28	68.99	0.79
4/29-4/9	115.72	-88.61	95.30	0.75*	-86.49	95.30	0.75*
5/13-4/30	88.78	-86.54	89.98	0.97	-86.54	89.98	0.97
5/28-5/14	102.50	-103.04	98.88	1.01*	-103.04	98.88	1.01*
6/10-5/29	79.79	-92.44	92.18	1.16	-92.44	92.18	1.16
6/24-6/11	92.48	-75.88	76.55	0.82*	-75.88	76.55	0.82*
7/3-6/25	66.22	-82.64	62.03	1.24			
7/22-7/5	118.89	-80.68	85.72	0.68*			
7/30-7/23	54.70	-50.38	51.53	0.93			
10/8-7/31	399.52	-122.54	117.22	0.31			
10/8-6/24	639.33				-153.93	141.26	0.24
10/29-10/9	79.95	-53.32	55.25	0.67*	-62.10	60.50	0.81*
Total	1431.67	-1009.82	991.07	0.71	-834.16	821.18	0.58

* = Interval includes harvest.
R = Over 10 mm rain in this period.
Water to establish stand 345.81 mm (Oct. 23, 1990 until Feb 4, 1991).

Table 3.(Continued) CIMIS ETr, water extraction from 122 cm soil profile during intervals between irrigations, water replacement at the end of the interval and ratio of water extracted to CIMIS ETr in 1992.

Interval Dates	ETr	Optimum Stress Water Extract	Optimum Stress Water Replaced	Optimum Stress Extract ETr Ratio	Minimum Stress Water Extract	Minimum Stress Water Replace	Minimum Stress Extract ETr Ratio
	mm	mm	mm		mm	mm	
2/4-10/30	196.56	-136.00	101.32	0.69*R	-139.24	103.41	0.70*R
3/24-2/5	158.55	-95.38	97.33	0.60*R	-100.75	106.23	0.64*R
4/27-3/25	186.48	-164.09	95.38	0.88*R	-160.35	90.21	0.86*R
5/11-4/28	87.83	-73.89	75.73	0.84	-79.67	66.6	0.91
6/26-5/12	91.81	-71.13	81.32	0.71*	-74.21	78.02	0.74*
6/9-5/27	98.17	-95.03	95.94	0.97	-95.38	96.61	0.97
6/22-6/10	99.85	-82.17	69.21	0.82*	-85.22	66.61	0.85*
7/6-6/23	122.43	-89.99	95.51	0.74	-87.31	88.49	0.71
7/21-7/7	115.67	-91.20	91.74	0.79*	-97.06	82.80	0.84*
7/28-7/22	53.76	-50.19	47.10	0.93	-47.53	47.77	0.88
8/17-7/29	128.03	-90.14	84.12	0.70*	-89.73	93.99	0.70*
8/24-8/18	42.27	-42.06	38.58	1.00			
9/8-8/25	96.36	-76.25	73.70	0.79	-100.34	92.50	1.04
9/22-9/9	71.55	-59.15	46.46	0.83*			*
9/30-9/23	42.48	-16.36	22.74	0.39	-78.22	61.89	0.69
10/12-10/1	57.00	-31.57	44.73	0.55	-27.60	38.19	0.48
11/11-10/13	83.42	-76.64	64.99	0.92*R	-75.74	77.54	0.91*R
12/15-11/12	64.01	-73.06		1.14R	-62.99		0.98R
1992 Total	1796.23	-1414.3	1225.9	0.79	-1401.34	1190.86	0.78
2-year Total	3227.90	-2677.8	2494.92	0.83	-2615.93	2394.05	0.81

1992		Short Stress			Long Stress		
2/4-10/30	196.56	-136.54	104.30	0.69*R	-149.67	114.00	0.76*R
3/24-2/5	158.55	-100.96	108.11	0.64*R	-110.44	101.17	0.70*R
4/27-3/25	186.48	-130.76	90.78	0.70*R	-128.21	113.42	0.69*R
5/11-4/28	87.83	-76.69	71.07	0.87	-76.67	72.61	0.87
5/26-5/12	91.81	-69.41	77.84	0.70*	-73.22	85.94	0.73*
6/9-5/27	98.17	-93.61	90.42	0.95	-101.23	97.83	1.03
6/22-6/10	99.85	-77.24	63.68	0.77*	-84.00	72.23	0.84*
7/7-6/23	122.43	-83.60	80.61	0.68			
7/21-7/7	115.67	-80.55	89.48	0.70*			
7/28-7/22	53.76	-55.22	46.11	1.03			
9/30-7/29	380.69	-127.55	70.90	0.34			
9/30-6/23	672.55				-132.02	127.07	0.20
10/12-10/1	57.00	-21.30	31.33	0.37	-21.73	28.80	0.38
11/11-10/13	83.42	-60.48	60.41	0.73*R	-76.64	61.27	0.92*R
12/15-11/12	64.01	-63.02		0.98R	-67.94		1.06R
1992 Total	1796.23	-1176.93	985.04	0.66	-1021.77	874.34	0.57
2 Year Total	3227.90	-2186.75	1976.11	0.68	-1855.93	1695.52	0.57

* = Interval includes harvest. R = Over 10 mm rain in this period.

Table 3.(Continued) CIMIS ETr, water extraction from 122 cm soil profile during intervals between irrigations, water replacement at the end of the interval and ratio of water extracted to CIMIS ETr in 1993.

1993		Optimum Stress			Minimum Stress		
Interval	ETr	Water Extract	Water Replaced	Extract ETr Ratio	Water Extract	Water Replaced	Extract ETr Ratio
	mm	mm	mm		mm	mm	
3/1-12/15	162.50	-140.59	133.13	0.86R*	-138.84	134.17	0.86R*
3/30-3/2	132.09	-77.91	75.07	0.59*	-82.03	83.4	0.62*
4/6-3/31	41.41	-35.19	40.14	0.90	-35.06	31.82	0.85
4/23-4/7	109.52	-81.26	69.97	0.74*	-75.95	65.79	0.69*
5/3-4/24	69.49	-41.17	47.33	0.59	-47.67	46.31	0.69
5/24-5/4	144.55	-90.67	92.86	0.63*	-93.38	97.74	0.65*
6/1-5/25	63.13	-53.76	48.85	0.85	-48.87	45.16	0.77
6/21-6/2	157.05	-106.57	105.63	0.68*	-98.51	112.58	0.63*
6/30-6/22	70.16	-75.35	55.10	1.07	-75.95	51.52	1.08
7/19-7/1	144.87	-91.48	98.55	0.63*	-93.48	106.49	0.65*
7/26-7/20	49.28	-49.70	47.65	1.01	-48.45	44.35	0.98
8/16-7/27	163.36	-106.34	95.57	0.65*	-107.80	106.26	0.66*
8/30-8/17	87.97	-65.76	74.92	0.75	-57.72		0.66
9/7-8/31	51.30	-58.39	48.32	1.14			
9/7-8/17	139.27				-96.27	96.38	0.69
9/29-9/8	129.83	-86.84	89.95	0.67*			
9/30-9/8	134.44				-99.97	89.24	0.74*
10/11-9/30	58.09	-41.74	38.16	0.72			
10/11-10/1	53.48				-46.36	42.33	0.87
11/8-10/12	108.71	-77.96	88.58	0.72*	-81.24	85.27	0.70*
1993 Total	1743.31	-1280.68	1248.78	0.73	-1248.15	1238.81	0.72
3 Year Total	4971.21	-3958.48	3743.70	0.80	-3864.08	3632.86	0.78

1993		Short Stress			Long Stress		
3/1-12/15	162.50	-138.52	127.50	0.85R*	-140.38	133.39	0.86R*
3/30-3/2	132.09	-73.29	74.69	0.55*	-78.14	76.04	0.59*
4/6-3/31	41.41	-35.76	35.56	0.86	-40.01	34.36	0.97
4/23-4/7	109.52	-83.35	79.27	0.76*	-78.76	77.42	0.72*
5/3-4/24	69.49	-45.32	46.09	0.65	-51.62	50.30	0.74
5/24-5/4	144.55	-87.84	94.54	0.61*	-96.12	111.28	0.66*
6/1-5/25	63.13	-47.27	43.39	0.75	-59.58	54.04	0.94
6/21-6/2	157.05	-106.73	110.62	0.68*	-110.85	113.02	0.71*
6/30-6/22	70.16	-60.91	51.83	0.88			
7/19-7/1	144.87	-101.29	102.62	0.70*			
7/26-7/20	49.28	-46.76	47.52	0.95			
9/30-7/27	437.07	-137.74	127.66	0.32			
9/30-6/22	701.38				-170.11	124.52	0.24
10/11-10/1	53.48	-45.74	39.15	0.86	-19.77	27.1	0.36
11/8-10/12	108.71	-74.05	76.65	0.68*	-56.39	62.92	0.52*
1993 Total	1743.31	-1084.57	1057.09	0.62	-901.73	864.39	0.52
3 Year Total	4971.21	-3263.91	3033.20	0.66	-2757.66	2559.91	0.55

* = Interval includes harvest. R = Over 10 mm rain in this period.

the same interval. In the column of interval dates the second date is the earliest day of the interval and is the irrigation date when the water was replaced for the previous interval. It is clear when comparing irrigation intervals with and without cutting alfalfa, the cutting had reduced evapotranspiration. In the intervals of the optimum treatment that did not have a harvest, there was an increase in the extract/ETr ratios until the end of June and then a decline. The ratios were further reduced by the irrigation treatments as they added drought stress to the plants up until the end of the treatments in October.

In Figure 5 is shown the comparative amount of water extracted from the 122 cm (4 foot) soil profile by the four irrigation treatments.

Soil saturation extracts corrected to field capacity indicating salt and chloride contents in 1993 are presented in Figure 6 in 30 cm (1 foot) depth increments for the irrigation treatments. Note that most of the salt buildup occurred in the 62-92 cm (third foot) layer where the texture changed from clayey to sandy. Analysis of variance was conducted on the concentrations and on the changes from one sampling date to the next for each soil level (Table 4) for 1991. The least significant difference (LSD) is given for each. The data present the conductivities before, during, and after the treatments. The last segment summarizes the change from the beginning to the end of the treatments. The initial concentrations on the deeper clay soil in the west side were significantly higher in all levels. The first segments from January and June show little of interest.

The June to October segment shows the long treatment increase in conductivity for the profile average to be significantly greater than the optimum and minimum treatments. The sandy layer below the upper 60 cm clay concentration at 60-90 cm exhibited a highly significant increase in salinity as compared to the other treatments. In the optimum treatment with the highest water application conductivity in the two lower layers actually declined. In the minimum treatment the lowest layer declined while the top three increased. In the short and long treatments the third layer accumulated more salinity than the optimum and minimum. The long treatment accumulated salinity in both the third and fourth depths. This is reflected in the overall significant differences in the profile averages.

In 1992 and 1993 the differences in salinity and chloride between the west and both the center and east locations were highly significant. Differences between the irrigation treatments were significant only after the full course of treatment in October as shown in Table 5. The chloride difference carried over until the February sampling in 1993. The conductivity and chloride contents are presented in four depth levels in Table 6. As was the case in 1991, the 62-92 cm depth exhibited the highest levels. This is the level where a transition from clay to sandier textures occurs.

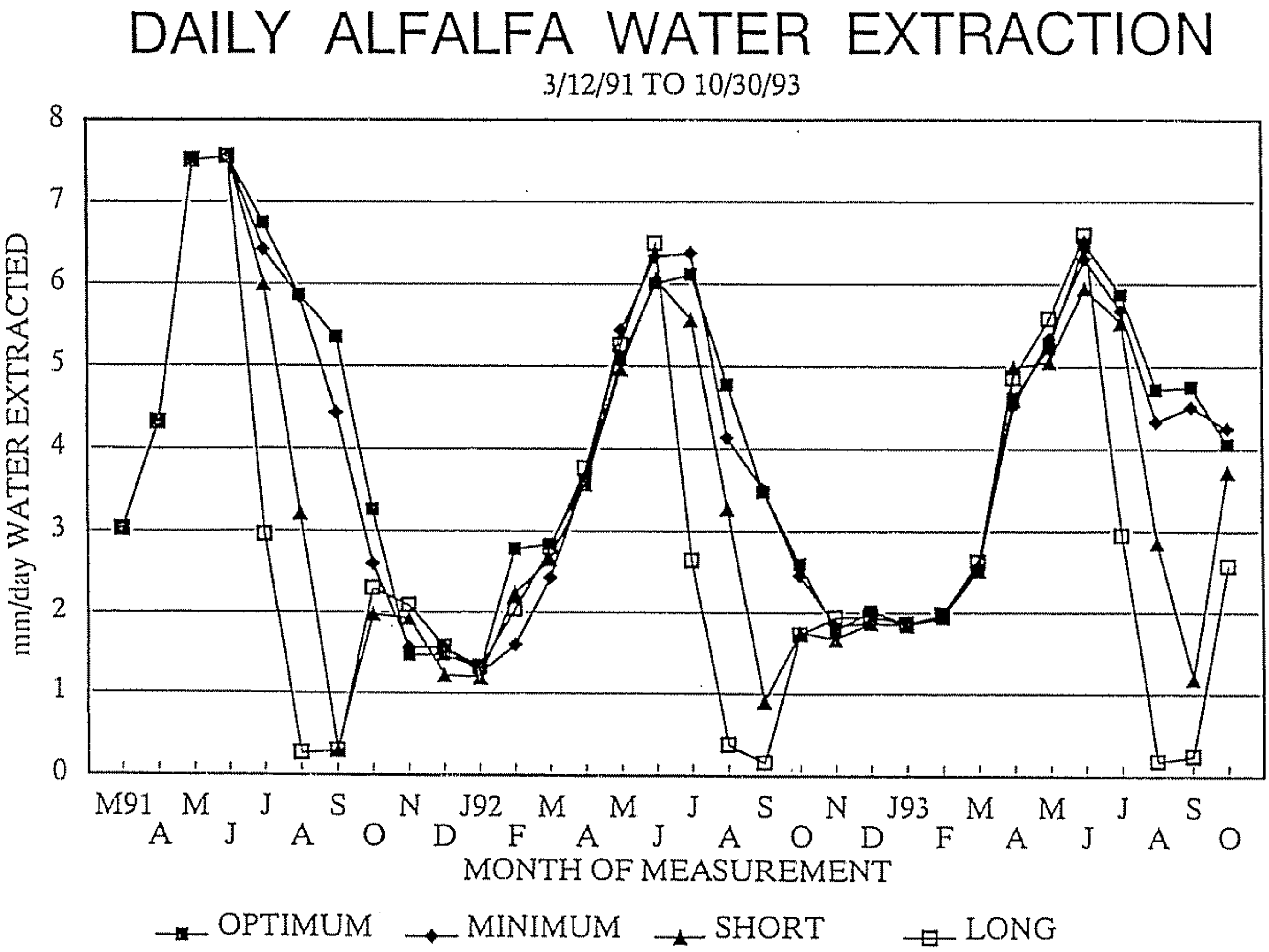
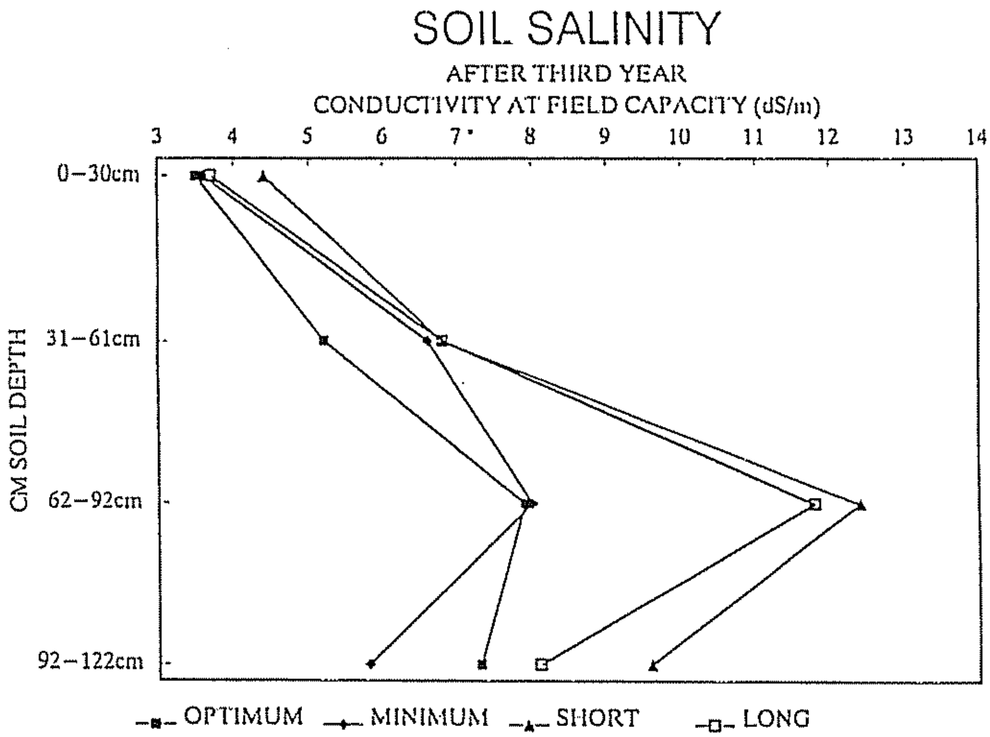


Figure 5. Water extracted from a 122 cm soil profile in 4 irrigation treatments.



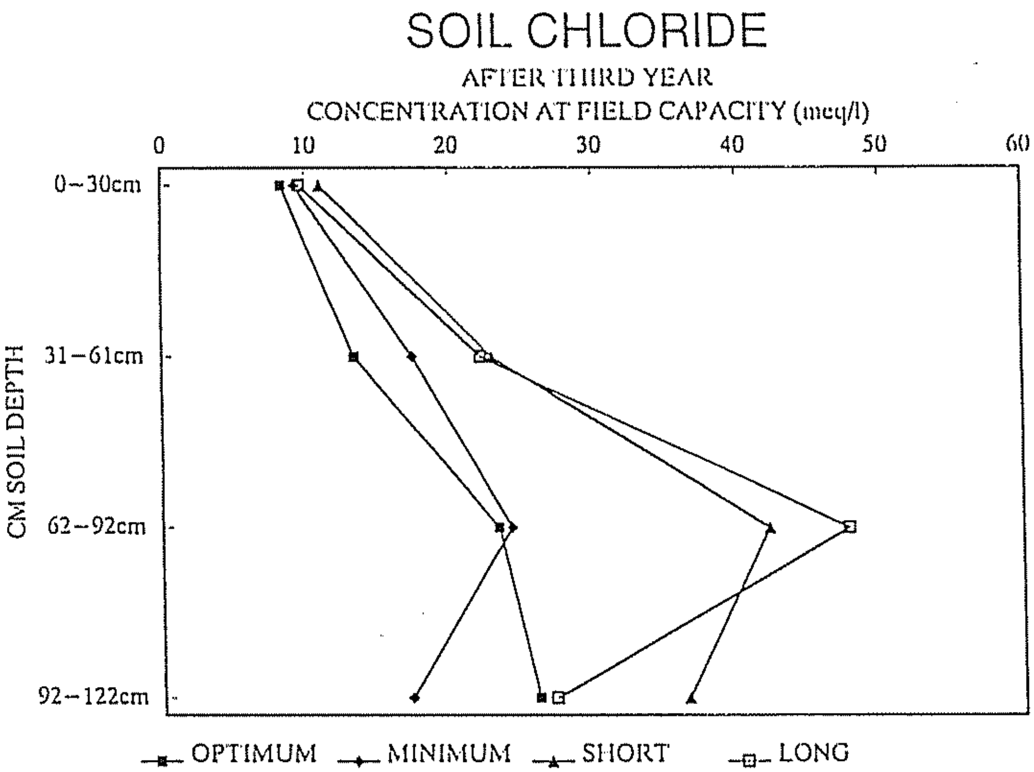


Figure 6. Average soil salinity and chloride concentration in 30 cm depths after four irrigation treatments.

Table 4 Initial soil saturation extracts at field capacity on east and west locations for four irrigation treatments.

Soil Depth	Location: West dS/m	Location: East dS/m	Irrigation Treatment: Optimum dS/m	Minimum dS/m	Short dS/m	Long dS/m	LSD 5%
January 2, 1991							
0-30 cm	5.7	2.6**	4.2	3.6	4.7	4.0	n.s
31-60 cm	8.3	2.1**	6.1	5.2	6.0	5.4	n.s
61-90 cm	13.3	4.0**	9.1	9.1	8.5	7.7	n.s
91-120 cm	9.8	4.3**	5.8	7.7	6.7	8.0	n.s
Average	9.2	3.5**	6.3	6.4	6.5	6.3	n.s
Saturation extracts at field capacity June 4, 1991 before treatment.							
0-30 cm	5.0	2.5**	4.1	3.6	4.0	3.4	n.s
31-60 cm	10.2	2.7**	6.6	5.5	8.4	5.4	n.s
61-90 cm	13.9	4.6**	9.6	9.2	10.5	7.7	n.s
91-120cm	8.9	4.7*	5.8	7.7	6.6	7.1	n.s
Average	9.5	3.6**	6.5	6.5	7.4	5.9	n.s
Saturation extracts at field capacity October 16, 1991 after treatment.							
0-30cm	6.1	2.7*	4.6	3.7	4.7	4.6	n.s
31-60cm	10.9	3.3*	6.7	6.5	9.0	6.2	n.s
61-90cm	16.3	6.3*	9.3	10.3	13.2	12.5	n.s
91-120cm	8.7	5.5	4.8	6.6	6.6	10.6	n.s
Average	10.5	4.5**	6.3	6.8	8.4	8.5	n.s
Change in salinity from June 4 to Oct.16,1991 during full treatment.							
0-30cm	1.1	0.2ns	0.5	0.1	0.7	1.3	n.s
31-60cm	0.7	0.6ns	0.1	1.0	0.6	0.9	n.s
61-90cm	2.3	1.8*	-0.3b	1.1b	2.7ab	4.8a*	3.4
91-120cm	-0.2	0.8*	-1.1b	-1.2b	0.0b	3.5a*	3.3
Average	1.0	0.9ns	-0.2b	0.3b	1.0ab	2.6a**	1.7

* Difference significant at 10% , ** 5 %, *** 1% .
Values followed by the same letter are not significantly different.
n.s = no significant difference.

Table 5. Conductivity and chloride concentration of saturation extracts at field capacity in 1992 & 1993. (Average 122 cm)

	Date conductivity sampled							
	1992				1993			
Location	3/20	6/5	8/13	10/20	2/16	6/8	8/24	10/19
	dS/m	dS/m	dS/m	dS/m	dS/m	Ds/m	dS/m	Ds/m
West	10.3a	10.0a	10.8a	10.1a	9.2a	8.4a	9.9a	10.1a
Center	5.9b	5.8b	5.2b	5.6b	5.5b	4.0b	6.1b	5.7b
East	5.7b	5.1b	4.8b	5.6b	4.6b	4.6b	5.0b	5.2b
LSD 5%	1.8	3.9	2.6	2.3	2.3	2.8	2.9	2.7
Irrigation Treatment								
Optimum	6.8	6.4	6.7	6.1b	3.7	5.2	6.6	6.0
Minimum	6.4	7.0	6.1	6.1b	4.1	4.9	6.4	6.0
Short	8.4	8.0	7.4	7.9ab	4.6	6.9	7.4	8.3
Long	7.6	7.4	7.6	8.2a	5.0	5.6	7.5	7.6
LSD 5%	n.s	n.s	n.s	2.0	n.s	n.s	n.s	n.s
Location	Chloride content							
	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l
West	41.3	40.5	43.4	39.5	31.2a	26.4a	37.2a	34.3a
Center	22.4	18.0	18.8	19.4	18.2b	11.2b	21.8ab	18.5b
East	20.9	15.9	17.3	19.3	11.5b	12.8b	14.5b	14.5b
LSD 5%	7.4	15.2	12.1	11.2	9.5	9.4	17.2	12.3
Treatment								
Optimum	25.2	19.9	24.9	21.5b	13.4b	15.6	22.4	17.8bc
Minimum	24.0	23.6	20.9	20.6b	16.7b	11.8	21.6	17.0c
Short	33.6	29.1	31.5	29.4a	25.3a	23.8	27.0	28.2a
Long	30.1	26.7	28.6	32.7a	25.9a	16.2	27.0	26.8ab
LSD 5%	n.s	n.s	n.s	8.25	8.25	n.s	n.s	9.2

Same letter in same column is not significant difference. n.s=not significant.

Table 6. Saturation extracts at four depths of four irrigation treatments on October 20, 1992 .

	Conductivity at field capacity				
Depth	Opt	Min	Short	Long	LSD 5%
cm	dS/m	dS/m	dS/m	dS/m	dS/m
0 - 30	3.5	3.9	4.2	3.9	n.s
31 - 61	5.6	6.0	7.4	7.8	n.s
61 - 92	8.9ab	8.0b	11.3ab	12.2a	3.66
92 - 122	6.4	6.5	8.7	8.8	n.s
Depth	Chloride content				
cm	meq/l	meq/l	meq/l	meq/l	
0 - 30	9.4	9.6	11.6	10.8	n.s
31 - 61	19.8	19.0	25.5	30.3	n.s
61 - 92	33.5b	30.5b	43.8ab	56.5a	14.3
92 - 122	23.3	23.4	36.7	33.4	n.s

n.s or same letter in same row = not significant difference.

WHITEFLY DAMAGE

During the 1991 season the silverleaf sweetpotato whitefly infested several field crops including alfalfa. On September 20, CUF 101 plots in all irrigation treatments were sampled for whitefly. Whitefly damage was assessed visually on October 21 using a five point scale on all varieties and treatments presented in Table 6 and visually in Figure 9. Nymphs, red-eyed nymphs, parasitized nymphs and empty nymphal cases were all significantly more numerous on the optimum and minimum treatments than on the short and long treatments. The visual damage was significantly greater on the two wettest treatments. This was believed to be a consequence of the drier condition of the stems and leaves of the drier treatments and the more succulent condition of the wetter treatments. The whitefly seem to have a preference for the more succulent plants and this could have been a benefit to the drier treatments. In this table can also be seen that the cultivars fell into three groups in whitefly tolerance. The most tolerant were CUF 101, UC Cibola, and UC 150; next was Moapa 69 and the least tolerant were Dofari, Mesilla, and Wilson. Natwick et al (1992 and 1993) using egg and nymph counts on the plots in this experiment found that the driest treatments had the least infestation and that the highest yielding cultivars were the most susceptible to whitefly infestation.

Table 7. White fly damage assessed visually on October 21,1991 using a five point scale.(1 = no damage and 5 = severe damage.)

	Irrigation Treatments								
Cultivars	Optimum		Minimum		Short		Long		Cultivar Means
Dofari	3.67	ab	3.89	a	2.56	efgh	2.78	ef	3.22 A
Mesilla	3.56	abc	3.67	ab	2.89	de	2.78	ef	3.22 A
Wilson	3.33	bc	3.44	bc	2.89	de	3.22	cd	3.22 A
CUF 101	2.78	ef	2.44	fghi	2.56	efgh	2.22	hijk	2.25 C
UC 150	2.67	efg	2.00	jk	2.11	ijk	1.89	k	2.17 C
UC Cibola	2.44	fghi	2.33	ghij	1.89	k	2.22	hijk	2.22 C
Moapa 69	2.22	hijk	2.67	efg	2.22	hijk	2.67	efg	2.44 B
Irrigation Mean	2.95	A	2.92	A	2.30	B	2.54	B	

LSD 5% 0.41 for interaction table, LSD 1% Irrigation means = 0.247
LSD 1% Cultivar means = 0.172

STAND

The number of plants per square meter or stand has a major influence upon yield. As seen in Table 7 the cultivar Dofari started and ended with the lightest stand. Within the cultivars the spread of stand differences noted in 1991 was leveled by the beginning of 1992. In 1992 the only cultivar stand difference was in Dofari, being lower than all the others. Only after the second season did the stands in the irrigation treatments show a significant difference with the wettest being highest and the driest being lowest as shown in Figure 7.

Table 7. Repeated stand counts taken from a 0.1 m^2 circle on each plot cultivars and irrigation prior to, during and after the completion of irrigation treatments.

	Alfalfa Stand Count (plants//m^2)								
	1991			1992			1993		
Source of Variation	5/6	7/16	10/28	5/20	7/20	11/5	5/7	7/21	10/25
Cultivar									
Wilson	260a	228ab	160ab	150a	150a	70a	72a	65a	43a
Moapa69	251ab	236a	155ab	140a	144a	75a	68a	71a	47a
Cibola	245ab	236a	178a	151a	153a	76a	70a	65a	47a
Mesilla	230bc	221ab	138b	141a	144a	63a	75a	64a	43a
CUF 101	228bc	221ab	150b	138a	137a	78a	68a	66a	43a
UC 150	218c	209b	159ab	140a	145a	75a	71a	66a	39a
Dofari	178d	173c	91c	75b	65b	26b	19b	15b	8b
LSD 5%	28	26	23	14	19	19	16	15	13
Irrigation									
Optimum	240	233	141	128	129	97a	91a	87a	64a
Minimum	222	207	147	134	133	87a	86a	75a	53a
Short	237	234	160	137	138	53b	46b	47b	24b
Long	221	198	140	135	133	27c	31b	26b	12b
LSD 5%	ns	ns	ns	ns	ns	25	23	21	13

ns = non-significant difference.

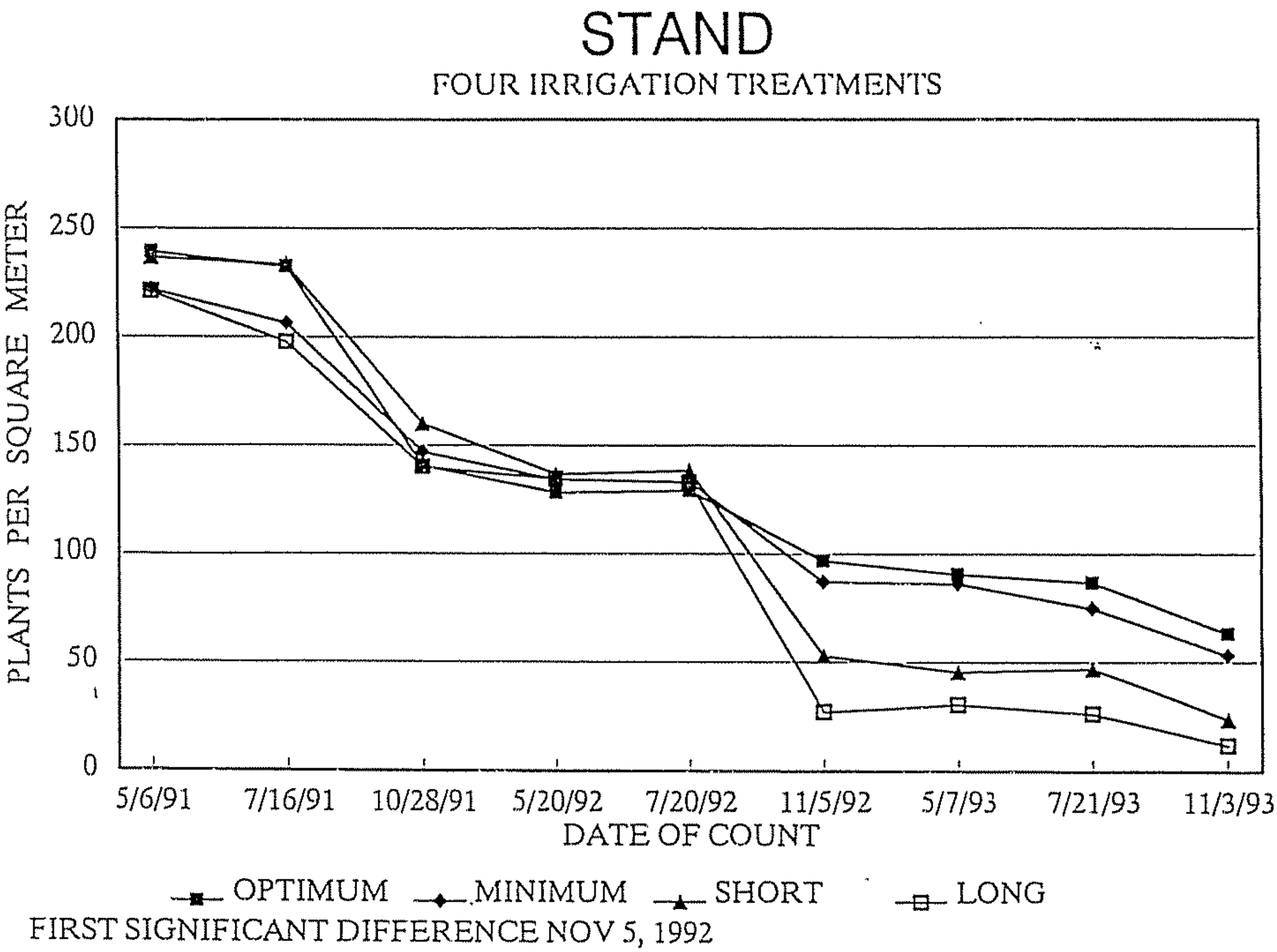


Figure 7. Stand reduction over three years with four irrigation treatments.

GROUND COVER

The amount of ground cover effects the ground temperature and therefore the rate of water evaporation from the soil surface. Table 9 presents the ratings of ground cover for comparison between irrigation treatments and cultivars. The effect of the irrigation treatments was first noted in July of the first year producing 10 ratings for the long treatment that had not been cut. At the end of the treatments in 1991, the long treatment had significantly less cover than the optimum and minimum and remained lower until the end of the trial. After the second years treatment both the long and short treatments were significantly lower that the wetter ones. In the cultivars Dofari had the least cover throughout reflecting the stand. CUF 101, UC Cibola, and UC 150 retained good cover through most of the trial. Moapa 69 and Wilson were in the best cover group the first year but slipped into the lower one during the second and third year.

Table 9. Degree of ground cover rating of seven alfalfa cultivars with four irrigation treatments on five dates 1991-1993. 10 = 100%, 1 = no cover.

Treatments	Degree of ground cover						
	4/19/91	7/16/91	10/21/91	7/27/92	3/30/93	7/26/93	11/3/93
Irrigation							
Optimum	8.37	8.24 b	8.83 a	7.56 a	7.18 a	6.81 a	6.02 a
Minimum	8.40	8.32 b	7.89 ab	7.65 a	6.44 a	6.29 a	4.84 b
Short	8.16	8.27 b	8.16 a	7.22 ab	4.51 b	4.33 c	3.47 c
Long	8.25	9.99 a	6.59 b	6.78 b	4.14 b	5.38 b	3.13 c
LSD 5%	n.s	0.23	1.33	0.49	0.89	0.75	0.89
Cultivars							
Cibola	8.92 a	9.03 a	8.61 ab	8.14 a	6.72 a	6.92 a	5.44 a
CUF 101	8.72 a	8.91 ab	8.28 ab	7.97 ab	6.31 ab	6.53 a	4.75 b
UC 150	8.69 ab	8.61 c	8.56 ab	7.81 b	6.67 a	6.72 a	4.75 b
Moapa 69	8.61 ab	8.97 ab	8.25 ab	7.83 b	6.03 bc	6.00 b	4.78 b
Wilson	8.22 bc	9.08 a	9.11 a	7.67 b	5.94 bc	6.03 b	4.75 b
Mesilla	7.78 c	8.72 bc	7.19 b	7.11 c	5.69 c	5.86 b	4.53 b
Dofari	7.11 d	7.61 d	5.06 c	4.58 d	1.61 d	1.86 c	1.56 c
LSD 5%	0.49	0.27	1.84	0.31	0.53	0.48	0.56

Values followed by the same letter in the same column are not significantly different.
n.s = non-significant difference.

PLANT HEIGHT

Plant height served as an general indicator of yields as shown in Table 10. Tallest plants during the year coincided with the highest yields: June and July in 1991, May and June in 1992 and May June and July in 1993. During the first year it appeared that in the period after the treatments ended there was a stimulation of growth in the drier treatments. This did not persist after the first year. Height measurements in July, August and September for the long treatment and in August and September on the short treatment were on unirrigated and unharvested plants and were therefore not representative of regrowth as in the optimum and minimum treatments. Comparing height there were three groups in cultivars. CUF 101, UC cibola and UC 150 the tallest; Wilson and Mesilla the shortest; and Dofari and Moapa 69 in the top and sometimes in the shortest group.

Table 10. Height of seven alfalfa cultivars with four irrigation treatments prior to harvest, in 1991,1992,1993.

Treatments	Height in cm								
1991		4/15	5/20	6/17	7/16	8/12	9/18	10/21	12/3
Optimum		42.5	35.1	60.7	59.5	44.0	42.5a	38.7a	25.3bc
Minimum		43.0	34.8	60.6	59.5	43.5	37.6b	31.7c	24.9c
Short		42.9	34.3	61.8	59.1	43.8		34.9b	26.7ab
Long		43.3	37.5	62.7				32.2bc	26.9a
LSD 5%		n.s	n.s	n.s	n.s	n.s	2.9	2.8	1.6
Cultivars									
CUF 101		47.1a	39.4a	64.2a	62.8a	46.7a	41.1a	37.1ab	31.1b
UC 150		45.5b	38.5a	63.1a	61.9a	46.6a	41.4a	37.8a	32.9a
UC Cibola		44.6b	38.1a	62.9a	61.6a	45.9ab	40.8ac	35.9bc	29.0c
Dofari		44.3b	32.6b	62.9a	58.7b	44.6b	39.8ac	32.8d	32.9a
Moapa 69		41.1c	33.8b	61.3b	61.1a	45.2ab	41.1ab	35.4c	27.5d
Wilson		39.5d	32.6b	57.4c	54.6c	38.4c	38.3bc	30.0f	14.4e
Mesilla		38.3d	32.8b	58.4c	54.8c	38.9c	38.2c	31.4e	13.8e
LSD 5%		1.4	1.7	1.6	1.9	1.8	2.8	1.3	1.1
1992	1/22	3/11	4/20	5/18	6/16	7/14	8/11	9/16	11/2
Optimum	20.5a	45.6	38.3	56.8	53.6	37.5a	34.0a	24.0b	39.0
Minimum	19.2b	43.1	37.4	55.4	51.0	35.1a	30.8b	19.2c	33.4
Short	19.1b	44.1	38.4	55.9	50.7	34.5a	30.3b	29.8a	34.2
Long	18.5b	43.9	36.9	55.2	49.5	29.6b	28.9b	29.3a	35.4
LSD 5%	0.86	n.s	n.s	n.s	n.s	3.0	2.5	2.3	n.s
Cultivars									
CUF 101	24.1c	48.4a	39.0	58.5a	54.3a	36.9a	32.9a	27.0ab	38.2a
UC 150	26.5b	48.5a	38.4	57.0ab	53.7ab	36.3ab	32.8ab	27.6a	38.4a
Cibola	21.4d	46.2b	38.3	56.8b	53.6ab	36.2ab	32.8ab	26.9ab	37.2ab
Dofari	34.1a	44.6c	37.0	56.7b	52.9ab	34.6b	31.3bc	25.2c	34.9c
Moapa69	19.2e	42.7d	37.1	55.7b	52.0b	34.7b	31.1c	25.9bc	35.6bc
Wilson	5.0f	39.0e	37.2	52.9c	46.1c	30.5c	28.1d	22.9d	31.5d
Mesilla	4.8f	39.6e	37.2	53.3c	45.8c	29.9c	28.1d	23.4d	32.7d
LSD 5%	1.1	1.5	n.s	1.6	1.9	1.8	1.6	1.6	2.2
1993	2/5	3/17	4/19	5/18	6/15	7/12	8/11	9/16	10/25
Optimum	30.7a	32.2	39.9	54.0	52.0a	50.5a	37.7b	31.4c	30.2a
Minimum	27.7ab	30.4	36.5	49.4	46.8b	45.4b	33.0c	23.2d	26.6b
Short	24.3b	29.5	35.7	50.9	50.1ab	48.9ab	48.9a	35.7b	26.6b
Long	29.7a	32.0	39.2	53.4	53.1a	46.2b	46.2a	43.4a	23.9b
LSD 5%	3.7	n.s	n.s	n.s	4.5	4.3	4.4	3.6	3.0
Cultivars									
CUF 101	32.2ab	34.9a	42.6a	55.0ab	54.1a	50.1a	43.7a	35.4a	29.5a
UC 150	35.2a	36.1a	42.3a	54.7ab	53.1a	49.2a	43.3bc	34.8b	27.6bc
Cibola	33.1ab	35.2a	41.8ab	55.6a	53.9a	50.6a	44.2a	36.0a	29.1ab
Dofari	25.3c	25.4c	25.1d	43.1c	41.1c	40.3b	35.6d	28.6c	24.6d
Moapa	30.7b	30.9b	38.5bc	52.9ab	53.6a	50.0a	43.8a	34.5ab	27.3c
Wilson	20.9d	27.5bc	37.8c	51.5ab	49.7ab	47.1a	40.0bc	32.4b	24.2d
Mesilla	19.1d	27.1c	36.8c	50.8b	48.1b	46.9a	39.4c	32.2b	25.5d
LSD 5%	3.2	3.5	3.7	4.5	4.6	4.0	3.6	2.9	1.8

Values followed by the same letter in the same column are not significantly different. n.s = non-significant difference.

WEEDS

In the growth that followed the end of the treatment period there was an obvious difference in the weed population. Weeds in each plot were counted on December 21, 1991 and analyzed via analysis of variance. A significant interaction between irrigation treatments and cultivars was observed. The result is shown in Table 11 and visually in Figure 11. The cultivars that had the least ground cover and the two driest irrigation treatments developed the largest weed population.

Table 11. Number of weeds per plot on December 21, 1991, two months after completion of the four irrigation treatments on seven alfalfa cultivars.

	Irrigation Treatments				
Cultivars	Optimum	Minimum	Short	Long	Cultivar Means
Dofari	17 de	27 de	102 b	140 a	72 A
Mesilla	16 de	10 de	63 c	64 c	38 B
Wilson	14 de	10 de	86 bc	23 de	33 B
CUF 101	5 de	2 de	31 d	12 de	13 C
U.C. 150	5 de	1 e	8 de	13 de	7 C
UC Cibola	3 de	1 e	18 de	14 de	9 C
Moapa 69	3 de	2 e	11 de	27 de	11 C
Irrigation Mean	9 B	8 B	45 A	42 A	

LSD 5%:Interaction table 25.0, Cultivar means 14.4, Irrigation means 31.9

DRY WEIGHT YIELDS

Dry weight yields are shown for the treatments and cultivars in Table 12 and Table 13. Blank spaces in the table indicate that no harvest was taken in that treatment while it was not being irrigated. LSD's in the columns with blank spaces were calculated only on the data shown in the table and did not include the blanks as zero. The irrigation treatments produced a significant annual yield difference in each treatment. Individual harvests became significantly different after the beginning of the treatments at the end of June. Yields after the first irrigation at the end of the dry treatments were still depressed. However, the following harvest in December 1991 showed a significant increase in yield above the wetter treatments similar to the height result suggesting that there had been no permanent harm to the drier treatments and that an actual stimulation occurred in the subsequent growth. This same stimulation after irrigation of the driest treatments was not evident in the 1992 and 1993 harvests reflecting the significant reduction in stand that had developed by this time. For the most part the cultivars fell into the same yield sequence as shown in the whitefly tolerance. This yield sequence was established before the whiteflys showed up so they may have contributed to the sequence of differences in yield but they did not cause it. The first group including CUF 101, UC Cibola, and UC 150: the second Moapa 69; third Mesilla and Wilson, and last Dofari. These differences were suppressed during the treatment harvests in July August and September, but reappeared in the first cutting after the end of the treatments in October. Mesilla and Wilson showed a depressed growth in December as is normal for dormant varieties.

Table 12. Average dry weight yield of seven alfalfa cultivars in four irrigation treatments 1991 to 1993

Dry weight yield in t/ha

1991

Treatments	4/17	5/21	6/18[1]	7/16[2]	8/13[3]	9/18	10/22	12/5	Total
Optimum	1.54	1.41	2.35	2.35	1.52	1.54a	1.25a	0.54a	12.51a
Minimum	1.56	1.34	2.31	2.32	1.53	1.25b	0.81b	0.52a	11.64b
Short	1.49	1.38	2.43	2.36			0.67c	0.62b	8.95c
Long	1.55	1.44	2.47				0.57c	0.63b	6.66d
LSD 5%	n.s	n.s	n.s	n.s	n.s	0.16	0.13	0.07	0.80

1992

Treatments	1/22	3/12	4/20	5/19	6/17[1]	7/14[2]	8/11[3]	9/16	11/13	Total
Optimum	0.42	1.33	1.29	1.85	1.97	1.35	1.03a	0.63a	0.86a	10.70a
Minimum	0.36	1.27	1.26	1.82	1.83	1.20	0.88b	0.39b	0.66b	9.66b
Short	0.42	1.28	1.31	1.76	1.81	1.16			0.31c	8.05c
Long	0.39	1.32	1.29	1.75	1.81				0.32c	6.87d
LSD 5%	n.s	n.s	n.s	n.s	n.s	n.s	0.13	0.11	0.15	0.85

1993

Treatments	2/6	3/17	4/20	5/19	6/15[1]	7/12[2]	8/10[3]	9/21	10/26	Total
Optim	0.71ab	0.76	1.08a	1.51	1.51a	1.38	0.67a	0.88a	0.48a	8.99a
Minim	0.60bc	0.68	0.96ab	1.33	1.25b	1.11	0.47b	0.52b	0.38b	7.30b
Short	0.53c	0.59	0.81b	1.21	1.24b	1.12			0.21c	5.71c
Long	0.75a	0.69	0.92ab	1.34	1.32ab				0.14c	5.15c
LSD 5%	0.13	n.s	0.17	n.s	0.21	n.s	0.18	0.12	0.08	1.22

1. Analysis of variance with four treatments when four harvested.
2. Analysis of variance with three treatments when three harvested.
3. Analysis of variance with two treatments when two harvested.

Numbers followed by the same letter in the same column are not significantly different. n.s = non-significant difference.

Table 13. Average dry weight yield of seven alfalfa cultivars receiving four irrigation treatmenmts over three years.

Dry weight yield in t/ha

1991

Cultivars	4/17	5/21	6/18[1]	7/16[2]	8/13[3]	9/18	10/22	12/5	Total
CUF 101	1.81a	1.64a	2.73a	2.63a	1.75a	1.64a	1.00ab	0.83b	11.72a
UC 150	1.74a	1.59a	2.59ab	2.61a	1.73a	1.63a	1.04a	0.88a	11.49a
UC Cibola	1.79a	1.58a	2.61ab	2.58a	1.75a	1.61a	1.05a	0.75c	11.39a
Moapa 69	1.59b	1.42b	2.50b	2.62a	1.72a	1.63a	0.93b	0.68d	10.76b
Mesilla	1.33c	1.37bc	2.22c	1.96bc	1.24b	1.07b	0.62c	0.22g	8.40c
Wilson	1.43c	1.28c	2.28c	2.01b	1.26b	1.13b	0.66c	0.27f	8.68c
Dofari	1.04d	0.88d	1.78d	1.91c	1.24b	1.07b	0.46d	0.42e	7.14d
LSD 5%	0.09	0.15	0.15	0.22	0.13	0.14	0.08	0.077	0.47

1992

Cultivars	1/22	3/12	4/20	5/19	6/17[1]	7/14[2]	8/11[3]	9/16	11/13	Total
CUF101	0.66a	1.48a	1.36a	2.07a	2.18a	1.40a	1.10a	0.55ab	0.69a	10.32a
UC 150	0.68a	1.48a	1.37a	2.04ab	2.16a	1.43a	0.94bc	0.48b	0.67ab	10.18ab
Cibola	0.48c	1.41a	1.28a	2.02ab	2.10a	1.43a	1.00ab	0.49b	0.65ab	9.76bc
Moapa69	0.41d	1.28b	1.28a	1.94b	2.07a	1.40a	1.02ab	0.50b	0.60b	9.39c
Mesilla	0.00e	1.31b	1.26a	1.70c	1.59b	0.97bc	0.81d	0.47b	0.44c	7.68d
Wilson	0.00e	1.32b	1.29a	1.74c	1.63b	1.09b	0.87cd	0.47b	0.40cd	7.85d
Dofari	0.57b	0.80c	1.14b	1.06d	1.25c	0.93bc	0.96bc	0.61a	0.33d	6.63e
LSD 5%	0.04	0.08	0.11	0.11	0.12	0.14	0.12	0.10	0.09	0.52

1993

Cultivars	2/6	3/17	4/20	5/19	6/15[1]	7/12[2]	8/10[3]	9/21	10/26	Total
CUF101	0.91ab	0.88a	1.15a	1.58ab	1.57ab	1.48a	0.75a	0.76ab	0.41a	8.35a
UC 150	0.97a	0.87a	1.14a	1.56ab	1.53b	1.40a	0.57b	0.64cd	0.32bc	8.05ab
Cibola	0.86c	0.88a	1.17a	1.63a	1.66a	1.48a	0.72a	0.72bc	0.39a	8.42a
Moapa69	0.75d	0.76b	1.01b	1.50b	1.53b	1.42a	0.70a	0.72bc	0.36ab	7.66b
Mesilla	0.33e	0.53c	0.94b	1.26c	1.15c	1.03b	0.44c	0.63cd	0.25d	5.77c
Wilson	0.36e	0.59c	0.98b	1.35c	1.26c	1.16b	0.46bc	0.60d	0.27cd	6.21c
Dofari	0.33b	0.24d	0.22c	0.56d	0.61d	0.47c	0.34c	0.85a	0.14e	3.04d
LSD 5%	0.10	0.08	0.10	0.12	0.13	0.16	0.11	0.12	0.06	0.61

1.Analysis of variance with four treatments when four harvested.
2.Analysis of variance with three treatments when three harvested.
3.Analysis of variance with two treatments when two harvested.
Numbers followed by the same letter in the same column are not significantly different. n.s = non-significant difference.

As shown in Table 14 a significant interaction occurred in the full season cultivar yields. CUF 101, Mesilla and Wilson did not show a significant difference in yield between the Optimum and Minimum irrigation treatments. All other comparisons show significant differences between irrigation treatments and the four group sequence is the same as noted in Table 13. Yield of CUF 101 by date and irrigation treatment is shown in Table 15 for 8 cuttings in 1991 and 9 in 1992 and 1993. No cutting was taken in December 1992 because of rain. Table 16 is a summary of the total yield by cultivar and irrigation treatment. Trends established in 1991 continued in 1992 and 1993. The average daily yields by month for the four irrigation treatments of CUF 101 are presented in Figure 8. Figure 9 presents the daily yields of the optimum treatment along with the ETr.

Table 14. Total dry weight yield interaction between cultivars and irrigation treatments over three years.

Cultivars	Irrigation Treatments: Optimum		Minimum		Short		Long		Cultivar Means	
	t/ha		t/ha		t/ha		t/ha		t/ha	
1991										
CUF 101	14.54	a	13.66	ab	10.54	cd	8.13	e	11.72	A
UC 150	14.36	a	13.18	b	10.69	c	7.72	e	11.49	A
UC Cibola	14.62	a	13.24	b	9.93	cd	7.75	e	11.39	A
Moapa 69	13.52	ab	12.93	b	9.90	cd	6.68	fg	10.76	B
Wilson	10.77	c	10.09	cd	7.57	ef	6.30	g	8.68	C
Mesilla	10.15	cd	9.96	cd	7.64	e	5.85	g	8.40	C
Dofari	9.60	d	8.38	e	6.21	g	4.19	h	7.14	D
Means	12.51	A	11.64	B	8.95	C	6.66	D	9.94	
1991 + 1992										
CUF 101	27.17	a	24.64	bc	19.79	def	16.51	hi	22.03	A
UC 150	26.42	ab	23.84	c	20.97	d	15.58	ij	21.70	AB
UC Cibola	26.72	a	23.97	c	18.63	efg	15.60	ij	21.23	B
Moapa 69	25.07	bc	23.50	c	18.59	efg	13.37	klm	20.13	C
Wilson	20.23	de	18.93	efg	14.34	jkl	12.84	lm	16.58	D
Mesilla	19.11	efg	18.40	fg	14.74	jk	12.04	m	16.07	D
Dofari	17.74	gh	15.82	ij	11.78	m	8.69	n	13.51	E
Mean	23.21	A	21.31	B	17.00	C	13.53	D	18.76	
1991 + 1992 + 1993										
CUF 101	38.32	a	33.75	cde	26.82	ghi	22.64	klm	30.38	A
UC 150	36.41	abc	31.81	ef	29.12	fg	21.66	mno	29.75	A
UC Cibola	37.57	ab	32.96	de	26.13	hi	21.93	lmn	29.65	A
Moapa 69	35.36	bcd	32.29	e	25.23	ijk	18.33	p	27.80	B
Wilson	28.13	gh	25.78	hij	19.10	op	18.15	p	22.79	C
Mesilla	26.29	hi	24.59	ijkl	19.50	nop	16.99	p	21.84	C
Dofari	23.25	jklm	19.04	op	12.91	q	10.99	q	16.55	D
Mean	32.20	A	28.62	B	22.71	C	18.68	D	25.55	

LSD 5% 1991 interaction 0.94, cultivar means 0.47, Irrigation means 0.80
LSD 5% 1992 interaction 1.70, cultivar means 0.85, irrigation means 1.51
LSD 5% 1993 interaction 2.71, cultivar means 1.35, irrigation means 2.52

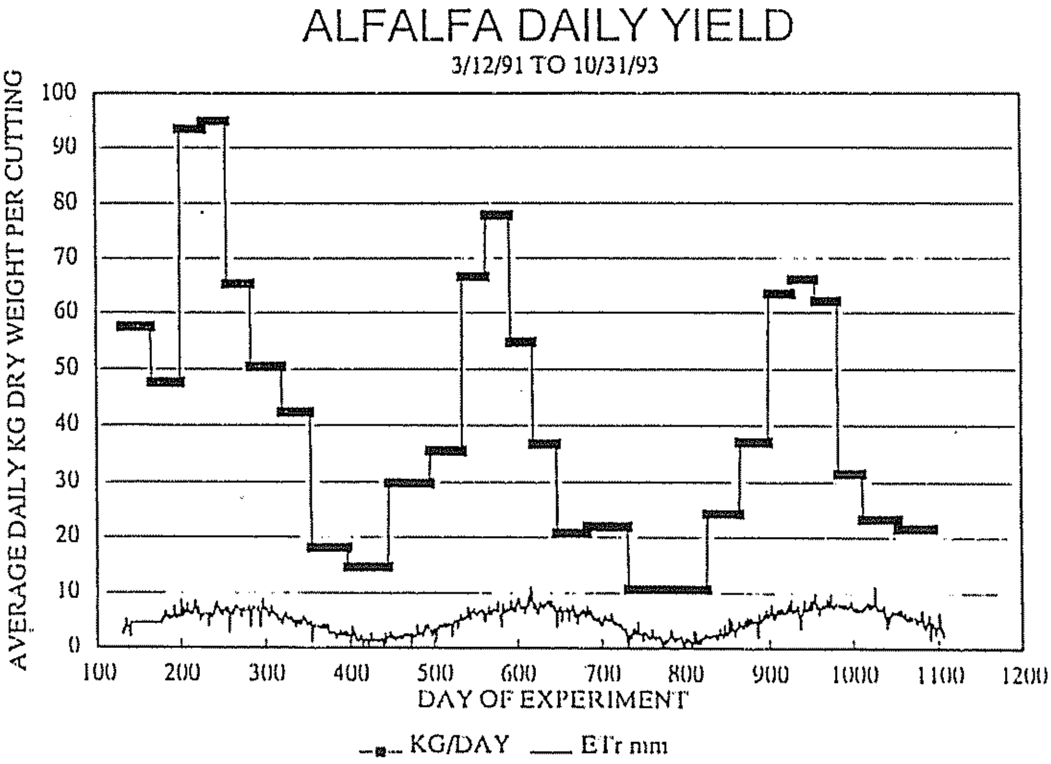


Figure 8. CUF 101 daily yield of Optimum treatment and reference evapotranspiration.

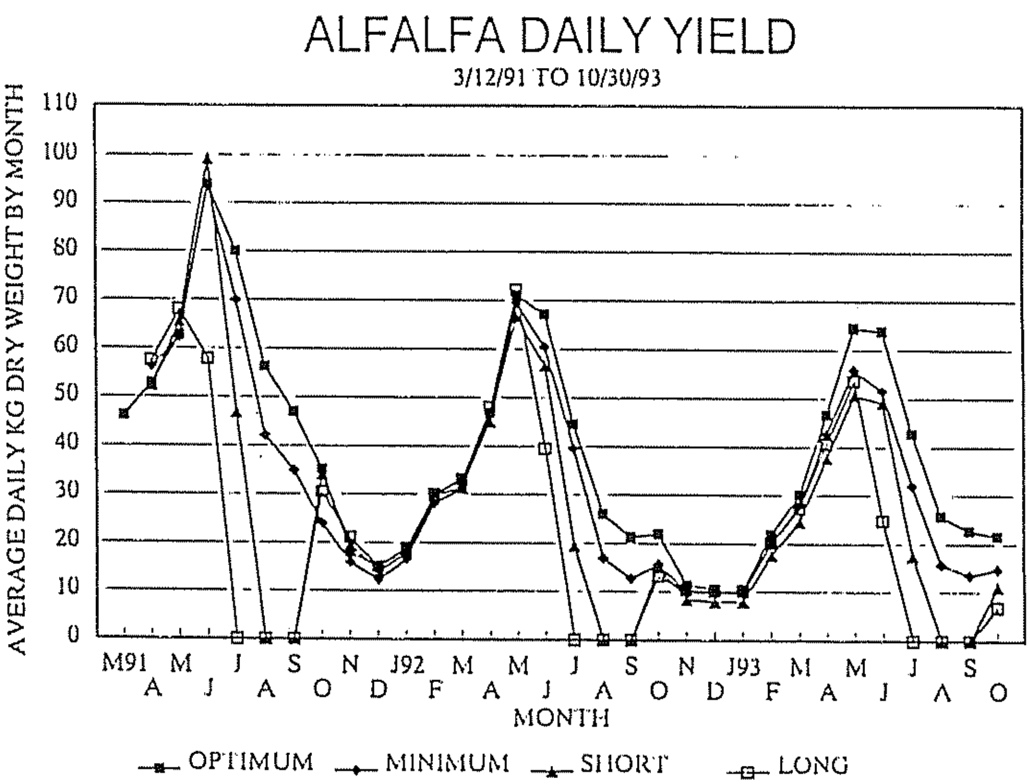


Figure 9. CUF 101 Average daily yield of four irrigation treatments.

Table 15. Dry weight yield of CUF 101 with four irrigation treatments in 1991, 1992 and 1993.

Dry weight yield in t/ha

1991

Treatments	4/17	5/21	6/18	7/16	8/13	9/18	10/22	12/5	Total
Optimum	1.71	1.62	2.61	2.66	1.83	1.82a	1.49a	0.80b	14.54a
Minimum	1.92	1.61	2.59	2.66	1.67	1.46b	0.96b	0.70c	13.66b
Short	1.72	1.59	2.89	2.62			0.85bc	0.87ab	10.54c
Long	1.90	1.73	2.86				0.72c	0.93a	8.13d
Mean	1.81	1.64	2.73	2.65	1.75	1.64	1.01	0.83	11.72
LSD5%	n.s	n.s	n.s	n.s	n.s	0.19	0.16	0.09	0.47

1992

Treatments	1/22	3/12	4/20	5/19	6/17	7/14	8/11	9/16	11/3	Total
Optimum	0.72	1.49	1.42	2.06	2.34	1.54	1.23a	0.75a	1.08a	12.63a
Minimum	0.58	1.41	1.32	2.08	2.09	1.41	0.97b	0.35b	0.77b	10.98b
Short	0.64	1.49	1.30	2.00	2.06	1.26			0.50c	9.25c
Long	0.69	1.52	1.39	2.13	2.22				0.43c	8.38c
Mean	0.66	1.48	1.36	2.07	2.18	1.40	1.10	0.55	0.70	10.32
LSD 5%	n.s	n.s	n.s	n.s	n.s	n.s	0.16	0.14	0.19	0.98

1993

Treatments	2/5	3/17	4/20	5/18	6/15	7/13	8/10	9/21	10/26	Total
Optimum	1.00a	0.97a	1.26a	1.78	1.85a	1.74a	0.88a	0.98a	0.69a	11.15a
Minimum	0.92a	0.89ab	1.17ab	1.59	1.53b	1.37b	0.62b	0.55b	0.48b	9.11b
Short	0.72b	0.79b	1.03b	1.42	1.42b	1.34b			0.28c	7.03c
Long	0.95a	0.89ab	1.12ab	1.51	1.49b				0.17c	6.13c
Mean	0.90	0.89	1.15	1.58	1.57	1.48	0.75	0.77	0.41	8.35
LSD 5%	0.21	0.16	0.19	n.s	0.26	0.28	0.16	0.21	0.11	1.21

Numbers followed by the same letter in the same column are not significantly different.
n.s = non-significant difference.

WATER USE EFFICIENCY

The yield produced per cm of water used is shown in Table 16. It is apparent that as the water application fell below the optimum need of the plant, the yield per unit of water declined. The data are presented to give the yield in terms of the water used to both establish and grow the crop during the harvest year. A breakdown of the effect of treatments on CUF 101 yields is presented in Table 17. Figure 10 presents data on kg/day yield, mm/day harvest and the kg/mm yield per unit water for the optimum irrigation treatment. In Figure 11 is the yield per unit water on a greatly expanded scale of all four treatments. Comparing the three years data it is apparent that water use efficiencies dropped from year to year. A major yield efficiency reduction began in all irrigation treatments in July of 1992. This coincided with a buildup of the silverleaf whitefly in June and July which may have caused the reduction. The drop in the optimum check suggests that something other than the irrigation was producing stress. Table 16 data provide some support that the likely source of stress was the whitefly since the driest treatment had the least yield reduction from 1991 to 1992 and also had the least whitefly damage. The further reduction in 1993 probably reflect the loss of stand seen in Table 7 and Figure 7. Data in both Table 16 and 17 indicate the best water efficiency was achieved by providing optimum amount of water to the alfalfa.

Table 16. Water efficiency of four irrigation treatments on CUF 101.

	Water Extracted			
Growth Phase	Optimum	Minimum	Short	Long
Establishment	mm	mm	mm	mm
10/23/90-2/5/91	345.81	345.81	345.81	345.81
Crop Growth Period				
2/5/91 - 12/5/91	1348.80	1299.71	1092.76	919.42
12/5/91- 12/15/92	1329.04	1316.22	1039.88	936.51
12/15/92-10/27/93	1249.80	1212.66	1048.85	877.49
2/5/91 - 12/15/92	2677.04	2615.93	2132.74	1855.93
2/5/91 - 10/27/93	3927.60	3828.59	3235.60	2733.42

	Yield of CUF 101			
Growth Phase	Optimum	Minimum	Short	Long
Crop Growth Period	t/ha	t/ha	t/ha	t/ha
2/5/91 - 12/5/91	14.54	13.66	10.54	8.13
12/5/91- 12/15/92	12.63	10.98	9.25	8.38
12/15/92-10/27/93	11.15	9.11	7.03	6.13
2/5/91 - 12/15/92	27.17	24.64	19.79	16.51
2/5/91 - 10/27/93	38.32	33.75	26.82	22.64

	Yield per unit of water used by CUF 101			
	Optimum	Minimum	Short	Long
	Kg/ha/mm	Kg/ha/mm	Kg/ha/mm	Kg/ha/mm
10/23/90 - 12/5/91	8.58	8.30	7.33	6.43
2/5/91 - 12/5/91	10.78	10.51	9.65	8.85
12/5/91 - 12/15/92	9.50	8.34	8.90	8.95
12/15/92 - 10/27/93	8.92	7.51	6.70	6.99
2/5/91 - 12/5/91	10.78	10.51	9.65	8.85
2/5/91 - 12/15/92	10.15	9.42	9.28	8.90
2/5/91 - 10/27/93	9.76	8.82	8.29	8.28

Table 17. Dry weight yields of CUF 101 per mm of water extracted for four irrigation treatments by year and month.

	Treatment											
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Year	kg/ mm	kg/ mm	kg/ mm	kg/ mm	kg/ mm	kg/ mm	kg/ mm	kg/ mm	kg/ mm	kg/ mm	kg/ mm	kg/
						Optimum						
1991			15.2	12.2	8.4	12.4	11.9	9.6	8.8	10.8	12.3	10.3
1992	14.7	10.7	11.8	13.0	14.0	11.2	7.3	5.5	6.1	8.5	6.4	5.3
1993	5.7	11.1	12.0	10.1	12.4	9.9	7.3	5.5	3.3	5.3		
						Minimum						
1991			15.2	13.0	8.3	12.4	10.9	7.2	7.8	9.2	10.2	7.9
1992	13.4	17.6	12.9	12.7	12.8	9.6	6.2	4.1	3.6	6.4	5.5	5.2
1993	5.3	10.4	10.8	9.4	10.5	8.2	5.6	3.6	1.9	3.5		
						Short						
1991			15.2	12.1	8.8	13.1	7.8	0	0	17.3	10.3	11.3
1992	15.2	13.2	11.8	12.6	13.4	9.3	3.5	0	0	8.6	5.1	4.3
1993	4.4	9.1	9.7	7.6	10.0	8.3	6.2	0	0	3.0		
						Long						
1991			15.2	13.3	9.0	7.7	0	0	0	13.2	10.1	9.5
1992	14.2	14.7	11.8	12.7	13.7	6.1	0	0	0	7.6	5.3	5.2
1993	5.4	10.3	10.4	8.4	9.6	3.8	0	0	0	2.7		

WATER AND YIELD EQUIVALENTS

A comparison of the total water saved by the irrigation treatments to the total yield lost over three years produces a yield equivalent in water. In Table 18 this comparison is presented for CUF 101. In this table the water saved was calculated at 65% efficiency. Using a more efficient irrigation method would reduce the water saving and increase the value of the water.

Table 18. Comparison of the optimum check irrigation to the other three treatments yield loss and water saving after one, two and three years.

Treatment Differential	Total Yield			Total Water			Ratio		
	One Year	Two Years	Three Year	One Years	Two Year	Three Years	One	Two	Three
	t/ac	t/ac	t/ac	ft ac	ft ac	ft	t/acft	t/acft	t/acft
Optimum - Minimum	0.39	1.07	1.98	0.27	0.32	0.51	1.44	3.34	3.88
Optimum - Short	1.79	3.20	5.04	1.30	2.49	3.51	1.38	1.29	1.44
Optimum - Long	2.86	4.67	6.93	2.17	4.15	6.12	1.32	1.13	1.13

In this analysis it is apparent that as the amount of water saved increased, the yield loss per unit of water declined.

The treatment followed in the past and the one most likely to be adopted by growers is the short treatment which had no irrigation applied in August or September. After one year the average loss per acre foot saved was 1.38 tons, after two years 1.29 tons and 1.44 tons after three years. At $100 per ton of alfalfa the values would be $138, $129 and $144 per acre-foot respectively.

The decline in yield from 1991 to 1992 and 1993 could have been due to the whitefly infestation that has caused great damage to the local industry. To the extent that this is the case, the effect on the yield/water ratios in Table 18 may not represent the result in a typical year without the whitefly. One could speculate that the stress from the whitefly added to the irrigation stress caused a greater reduction in alfalfa yield than would have the irrigation stress alone. This greater reduction in yield than in a typical year would result in an apparent higher value for water that in a "normal" year. The increase in the water value for 1993 probably is a result of this. The significant increase in salinity with decrease in water application will add to the cost of the drier water treatments due to the time and expense of leaching the salinity to its former levels or growing a crop such as sudan grass to facilitate salt leaching.

We conclude that when no irrigation was applied in August or September the yield of CUF 101 was reduced from 1.29 to 1.44 tons per acre for each acre-foot of water saved over the three year period from 1991 to 1993 .

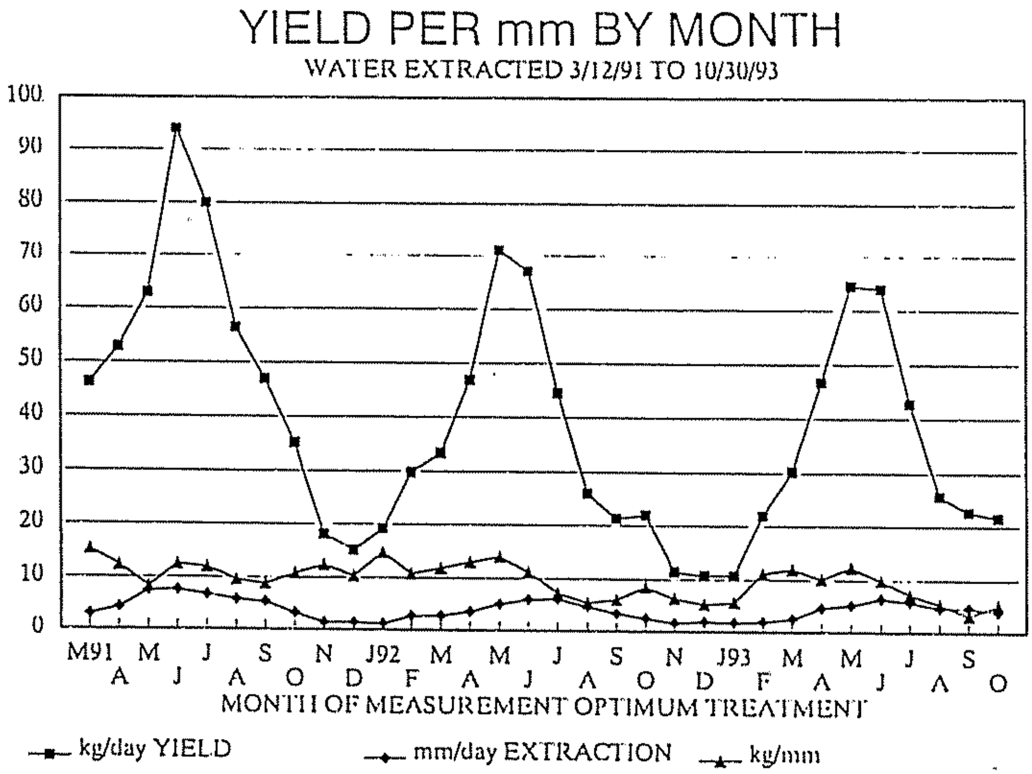


Figure 10. CUF 101 yield per day, mm per day extraction, kg yield per mm of water extracted by the optimum irrigation treatment.

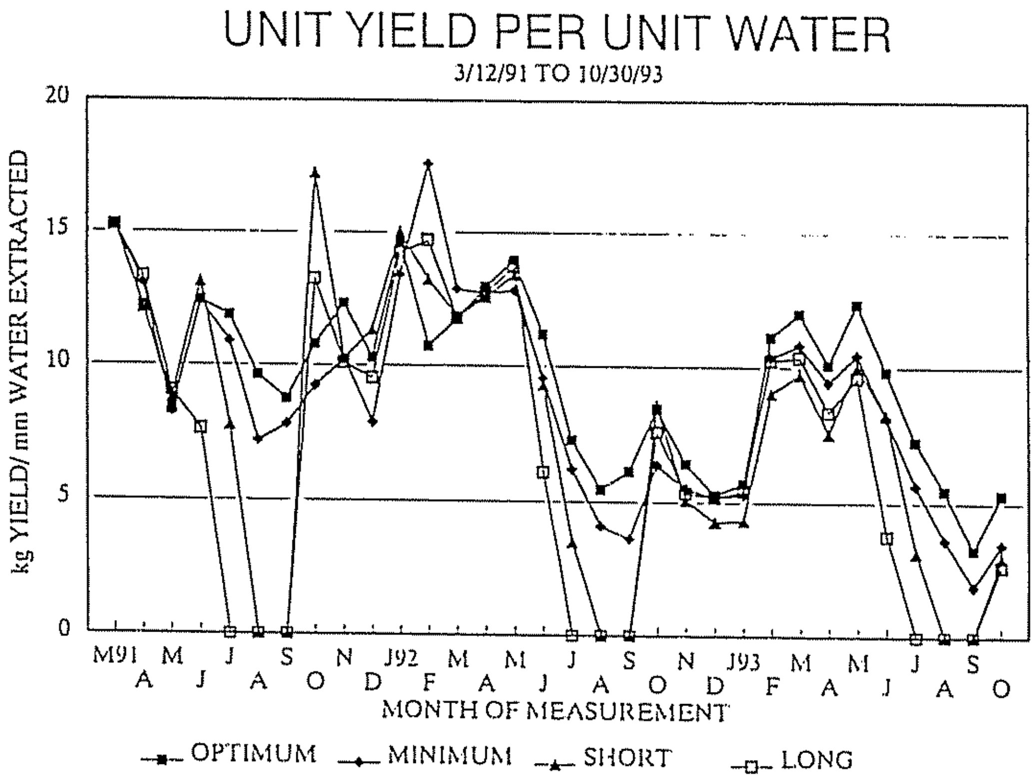


Figure 11. CUF 101 kg/mm yield of four irrigation treatments in three years

LITERATURE CITED

1. Birdsall, Stephen L, 1991, 1990 Agricultural Crop & Livestock Report, Imperial County. 150 North Ninth Street El Centro, CA 92243-2850.

2. Laemmlen, F.F., editor 1991. Guidelines to production costs and practices. Imperial county field crops circular 104-F. 1050 E Holton Road, Holtville, CA 92250.

3. Lehman, W.F., 1979. Alfalfa Production in the low desert valley areas of University of California. Berkeley CA 94720.

4 Natwick, E.T., Robinson, F.E.and Bell, C., 1992. Alfalfa irrigation practices and cultivar selection for sweetpotato whitefly management. 22nd California/Arizona Alfalfa Symposium Holtville CA December 9-10, 1992. pages 61-65.

5. Natwick, E.T., Robinson, F., 1993. Alfalfa host plant resistance to Silverleaf Whitefly (formerly Sweetpotato whitefly strain b). Proceedings Alfalfa Seed Production Symposium. Holtville CA. March 11, 1993. Pages 60-64.

APPENDIX A
FINAL REPORT 1993

SOIL EXCAVATION FOR ROOT EXAMINATION

Significant differences in both soil saturation extracts and soil chloride in tables 4 & 5 were associated with significant yield differences between the west location and the center and east locations. An LSD 5% of 2.18 t/ha from the three year total dry weight yield analysis of variance for the west location (21.58 t/ha), center (26.94 t/ha) and east(28.15 t/ha) indicated a significant difference between the west location and the other two. Fortunately the selection of the locations oriented north and south allowed a statistical isolation of the variance between the locations allowing measurement of confounding of the differences with the irrigation treatments. At the conclusion of the field experiment pits were dug to 180 cm depth in each optional treatment and each short treatment in each of the three locations. These 18 pits were examined for the root depth and condition and soil layers were sampled for saturation extract and soil chloride concentration at field capacity.

In the pits on the west location gypsum precipitated at the 45 to 60 cm depth in a dense clay layer that extended below to a sandy layer. At or slightly below the gypsum the salinity level increased significantly from about 6 dS/m to about 15 Ds/m. Soil chloride increased from about 20 meq/l in the root zone to about 70 meq/l below the roots. Many of the tap roots terminated in the top 30 cm exhibiting dead meristems black in color. Above the black tips lateral roots much finer in diameter than the tap root extended out and down below the tap root into the zone of higher salinity where they also stopped in or slightly above the gypsum precipitation. Fine roots in the upper zone grew on the surface of the dense clay peds resembling the restricted root growth against the inside of a flower pot.

In the center locations the short treatment tap roots terminated in the top 30 cm with laterals extending to the 60 cm depth into the top of a sandy layer. The salinity in the upper clay layer was 5.0 Ds/m (Cl 7 meq/l) or less in the root zone climbing to 6.0 Ds/m (Cl 40 meq/l) or higher where the roots stopped. The optimum treatment tap roots terminated deeper in the 60 cm depth range and had laterals to the 75 cm range. Salinity in the top clay layer was less than 5.0 Ds/m (Cl 7.0 meq/l) climbing above 6.0 dS/m (Cl 15.0 meq/l) where the roots stopped.

In the east location the clay layer was 68 cm deep above a sandy layer on the north and 41 cm above the sandy layer in the south. Both of these locations had rooting below 90 cm. The tap roots in the short treatment terminated at about 23 cm while the optimum treatment tap roots terminated about 48 cm with several extending down to 56 cm. Laterals were seen at 112 cm well into the sandy layer. Soil salinities were generally below 5.0 dS/m (Cl 15 meq/l) in the root zone. The east central replication had gypsum precipitation in both treatments. In the short treatment it occurred from the 25 to 69 cm depth and in the optimum treatment it was from the 56 to 76 cm depth. Roots terminated within the gypsum layer. Salinities were near 9.0 dS/m (Cl 20 meq/l) above the gypsum and 16 dS/m (cl 44 meq/l) in the gypsum layer where rooting stopped.

DISCUSSION

Judging from the variation in the soil profiles a question arises as to whether the observed differences were truly the result of the irrigation treatments or simply the reflection of the random soil conditions where the treatments happened to fall. Fortunately the optimum and short irrigation treatments fell adjacent in each replication with first one on the north and then the other. Soil conditions changed gradually from one area to another so that those in close proximity were quite similar for the comparison of the optimum and short treatments. The west location had tap root termination and lateral rooting at shallower depths than the center or east locations. But the optimum treatment had generally deeper rooting than the short treatment.

The presence of gypsum precipitation marked the upper zone of higher salinity. The resident high salinity was due to the massive poorly drained clay in the area. The higher ionic strength or concentration of salts caused the less soluble gypsum to precipitate. The root growth stopped as a result of the physical strength needed to penetrate the massive clay and of the high salinity levels. In all comparisons of the optimum and short treatments where gypsum occurred the upper boundary of the gypsum was deeper in the optimum treatment than in the short treatment indicating some result of the treatments. The shallower rooting above the gypsum produced better growth in the optimum treatment than in the short treatment due to the additional irrigation in August and September.

In the other locations where the gypsum did not occur rooting was deeper and the salinity did not increase as rapidly from the clay upper layer to the lower sandy layer.

CONCLUSION

There was a great variation in the soil profile in the field where the study was conducted. The three locations oriented north and south showed profile differences between the west with deeper more massive clay, higher salinity and shallower rooting than the central or east locations that had deeper rooting and lower salinity and chloride concentrations. The soils were similar within the north-south locations so that the greatest differences in soil were isolated by location and could be analyzed to measure confounding with the irrigation treatments.

We conclude that the treatment analysis was valid for soils with similar variations in texture, strength and salinity conditions common in Imperial Valley.

APPENDIX B
SOIL SALINITY RECLAMATION

The alfalfa plots were harvested one last time in December 1993 to remove all cover. The berms separating the plots were disked down and the entire experimental area deep chiseled. The soil was allowed to dry and was disked a second time. Berms were constructed in the north south direction to allow irrigation perpendicularly to the east-west orientation of the experiment. The plots were irrigated with an average of 7.18 inches (182 mm) on February 10 1994. Soil salinity samples were taken from the sites previously sampled for the alfalfa experiment. A summary of the soil salinity changes is presented in Table 1.

The data provide some interesting observations. The optimum treatment showed a slow decline in salinity from beginning to end of the experiment. This gives us confidence that the irrigation was adequate to meet the needs of both irrigation and leaching of salt. The minimum treatment showed a one time increase at the end of the first year of treatment. Both the long and short treatments jumped after one year of treatment and remained high through the second year of treatment when the stands dropped significantly. The short treatment remained high the third year, while the long treatment dropped probably due to the lower demand for water from the lower stand density allowing more water for leaching.

Table 20. Soil profile average saturation extracts (dS/m) at field capacity during and after the alfalfa experiment.

Period	Date	Opt	Min	Short	Long	Sig	Profile average
Start	1/2/91	6.3	6.4	6.5	6.3	n.s.	6.4
End 1st year	10/16/91	6.3	6.8	8.4	8.5	n.s.	7.5
End 2nd year	10/20/92	6.1	6.1	7.9	8.2	5%	7.1
End 3ed year	10/19/93	6.0	6.0	8.3	7.6	n.s.	7.0
Leaching	3/2/94	6.0	6.1	7.2	7.5	n.s.	6.7
Sudan cut	6/21/94	5.4	5.4	6.6	6.2	n.s.	5.9
Sudan cut	8/10/94	5.7	6.4	6.4	6.0	n.s.	6.1

After leaching the overall change in entire profile average from October 1993 until March 1994 was - 0.272 dS/m. The reduction took place primarily in treatment averages of the short and long treatments. But these two treatment averages still remained about 1 dS/m higher than at the start of the experiment. Sudan was planted to see if this would accelerate the overall salinity reclamation. The irrigation application was measured using head difference during irrigation of 12 inch outlets on the concrete ditch. Due to the spacing one of the checks was irrigated with four inch siphons. The three irrigations on the six checks were as follows: April 12,1994, 96 mm, May 5, 1994, 100 mm May 27, 1994, 155 mm. On June 16 the sudan was cut and June 21 soil salinity samples were taken in the same locations as previously. Irrigation of 163 mm was applied on June 27, 1994 after the harvest and of 155 mm on July 21, 1994. A final salinity sample was taken on August 10, 1994.

The salinity samples taken from the sudan show a drop in dS/m in all treatments after the first cut. The slight rise in conductivity after the second cut resulted from incomplete coverage of the tail end of the irrigation plots. An attempt had been made to prevent runoff and this led to the last row of plots in the minimum treatment receiving a light coverage with a subsequent increase in salinity.

We observed that the sudan grass growth had been effective in reducing soil salinity. The two highest salinities in the long and short treatments were brought down to or below the values at the beginning of the experiment. This demonstrated that where reduction of irrigation water below the optimum for three years in an alfalfa crop had caused an increase in soil salinity, a subsequent growth of sudan grass brought the soil salinity back to the beginning level.

IID-53 (R. 5-72) - MEMO AND REPLY

TO: Jesse Silva FROM: Tim O'Halloran

SUBJECT: Alfalfa Water Stress Report

MESSAGE: At this month's meeting of the Imperial Valley Conservation Research Center Committee, I received the attached Alfalfa Water Stress Management report. The principal author is Frank Robinson and the work was conducted at the Meloland Station. Funding for the work came from MWD. I am sending copies to you and Karen for your information and files. I will be reviewing the report and forwarding any comments to you.

DATE: December 28, 1994 SIGNATURE: Tim F. O'Halloran

REPLY: cc Karen McLaughlin

DATE: SIGNATURE:

Circulate in WR Reading file
then place in WR Library.
K.Sm
1/4/95